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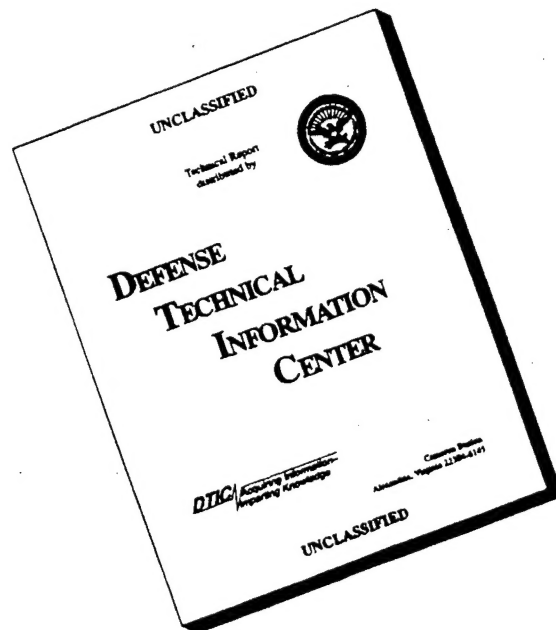EXPERIMENTAL DATA OBTAINED IN THE FIELD
PARTS I, II, AND III

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1951

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12 July 1995

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JOSEPHINE B. WOOD
Chief, Technical Support

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PARTS I, II, AND III

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Parts I, II, and III

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Scientific Director

Los Alamos Scientific Laboratory

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DOSIMETRY USING MICE

by

Ernest C. Anderson
Martha Benson
James T. Brennan
Robert E. Carter
Payne S. Harris

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Section 1

THE BIOLOGICAL EFFECTIVENESS OF INITIAL GAMMA RADIATION FROM AN ATOMIC WEAPON

By Robert E. Carter, Wright H. Langham, Ernest C. Anderson, George W. Taylor,
James T. Brennan, Payne S. Harris, Ernest A. Pinson, Theodoro T. Trujillo,
Robert L. Schuch, and Martha Benson

Acknowledgments

Abstract

Weight losses of the spleen and thymus of LAf_1 mice exposed to initial gamma radiation at varying distances from the atomic weapons used in Dog, Easy, and George Shots were determined. These changes were compared with weight losses of the spleen and thymus of LAf_1 animals exposed to various doses of 230-KVP X radiation in the control study.

Significant variations in the slopes of the regression lines, fitted to the control study data and to the data of each of the three field tests, could not be demonstrated. The biological data indicated a mean free path for the initial gamma radiation in substantial agreement with physical values. Hence, it was felt that scaling biological data for all three field tests to an arbitrarily selected weapon yield and accompanying gamma-ray flux was justified.

From the resultant composite curve, scaled to a weapon yield equal to that of the Dog Shot weapon, the biological effectiveness of the initial gamma radiation, in terms of roentgens (r) of 230-KVP X radiation required to produce a comparable effect, at varying distances (D) in yards from ground zero was found to be

$$\log (rD^2 \times 10^{-7}) = 4.1310 - 0.00119D \pm 0.041,$$

where 0.041 denotes the standard deviation from the regression (standard error of estimate).

No significant variation between the curve representing the biological effectiveness of the weapon radiation and a similarly constructed curve for data from National Bureau of Standards (NBS) film packs placed with the animals could be demonstrated. Thus, within the limits of uncertainty of the biological and film-badge data, the ratio of biological effectiveness of the initial gamma radiation from the weapons used and 230-KVP X radiation was seen to be essentially unity. This ratio involves the dependence of film-badge dose estimates on the calibration of the films themselves and, in the light of present information, must be considered singular to the film-badge dosimeters used in these tests.

Chapter 1

Introduction

1.1 PURPOSE OF EXPERIMENT

The measurement of splenic and thymic weight loss as a function of distance from an atomic explosion was included in Operation Greenhouse to gain information on the following subjects: (1) the biological effectiveness of initial gamma radiation from an atomic explosion as a function of distance from the explosion and as a function of weapon yield; and (2) the relation between the effectiveness of initial gamma radiation and conventional X radiation from laboratory sources. While extension of the data on the effect of various radiations on the spleen and the thymus to other biological systems is admittedly limited, the use of a relatively small segment of the biological effects capable of measure afforded several advantages in field studies. First, the indicator registered quantitatively over a comparatively wide range of total dose, minimizing the undesirable effects of variations in predicted weapon yield. Second, the experimental method was sufficiently simple to be carried out quickly and with a minimum of equipment and animals.

1.2 SUMMARY OF PREVIOUS COMPARABLE EXPERIMENTS

No previous nuclear weapon tests have included biological "dosimeters." Initial studies using weight change of the spleen and thymus of the mouse were conducted under laboratory conditions and were concerned with establishing the total dose range over which the indicator could be expected to function and with establishing the quantitatively similar response of the indicator to varying energies and types of radiation. This work was conducted with X rays of various energies and with neutrons from the thermal column of the Los Alamos "Water Boiler." [1-3]

---

[1] R. E. Carter, P. S. Harris, and J. T. Brennan, "The Effect of Acute Doses of X Irradiation on the Splenic and Thymic Weight of CF1 Female Mice," Los Alamos Scientific Laboratory Report LA–1075 (1950).

[2] J. T. Brennan *et al.,* "Change in the Weight of Spleen and Thymus of the Mouse after Exposure in a Thermal-neutron Column," Greenhouse Report, Annex 2.2, Part I.

[3] R. E. Carter, unpublished data.

Chapter 2

Basic Theory

2.1 SPLENIC AND THYMIC WEIGHT LOSSES IN MICE AS QUANTITATIVE BIOLOGICAL INDICATORS OF RADIATION DAMAGE

Reduction in the weight of various organs, especially the spleen, has been noted since the first biological experiments with ionizing radiations.[1] The extreme radiosensitivity of lymphatic tissue has been established,[2] and loss of lymphatic tissue mass occurs through destruction of lymphocytes and failure of replacement through damage to their precursors. Well-recognized histological changes occurring after exposure indicate that lymphatic tissue loss is responsible for essentially the entire weight loss of the thymus. While the thymus consists almost entirely of lymphatic tissue, only approximately 50 per cent of the spleen is made up of lymphocytes. Reduction of splenic weight in the lower dose ranges (up to 400 r) results partly from loss of lymphatic tissue, while over 600 r, red-pulp loss is the largest factor.[3] The large variation in lymphatic tissue content of the spleen [4] contributes to the larger variation found in the relation of dose to splenic weight loss as compared with thymic weight loss. The mechanism of weight loss of the spleen after destruc-

tion of the majority of lymphatic tissue is undoubtedly complex and has not been investigated adequately at the present time.

In the control and field studies, the data were represented by arbitrary mathematical equations so chosen as to give the best fit to the data with simple equations with a minimum number of parameters. For the thymus, an exponential function was adequate over the range 150 to 700 r, and by making a probit transformation of per cent thymic weight loss, the analysis could be extended to include 75 to 900 r. The best eye-fitted curve was drawn through the points representing the splenic data. No mathematical equation was calculated because of the large variation in the splenic response in LAf₁ mice.

2.2 DETERMINATION OF THE RELATIVE BIOLOGICAL EFFECTIVENESS OF INITIAL GAMMA RADIATION FROM AN ATOMIC WEAPON

Determination of the relative biological effectiveness of the initial gamma radiation from an atomic weapon as compared with conventional X radiation is based on the comparison of the slopes of the best lines of fit to the data over the dose range studied. If the curves representing the effects of two different radiations do not differ significantly in their slopes on a log dose plot, the ratio of the biological effectiveness between the two radiations is the ratio of doses required to produce equal effects in each instance.

The slope of the regression line of organ weight loss of log dose for the field experiments can be determined independently of the control study and without knowledge of the absolute dose received at any distance from

---

[1] Heineke, "Ueber die Einwerkung der Röntgenstrahlen auf innere Organs," *Munchener medizinische Wochenschrift,* LI (1904), 785.

[2] C. E. Dunlap, "Effects of Radiation on the Blood and Hematopoietic Tissues, Including the Spleen, Thymus and Lymph Nodes," *Archives of Pathology,* XXXIV (1942), 562.

[3] R. E. Carter, "Splenic Changes in CF1 Female Mice over a 41-day Period Post X Irradiation," Los Alamos Scientific Laboratory Report LADC–742 (1949).

[4] *Ibid.*

the weapon in the following manner. Using data on multiple scattering presented by Gray for aluminum [5] and by White for water [6] it can be shown that for the gamma-ray spectrum of an atomic explosion, the effect of multiple scattering and build-up on the apparent absorption coefficient can be neglected in air at distances greater than approximately 1,000 yd.[7] The dose of radiation, r, at any distance, D, greater than 1,000 yd, may be written as

$$r = \frac{ke^{-D/\lambda}}{D^2} \qquad (2.1)$$

where k is a constant dependent on the kilotonnage of the weapon and λ is the apparent mean free path of the gamma photons. Assuming that organ weight loss and dose follow the same relation in the field as was observed in the control studies, namely,

$$r = ab^w \qquad (2.2)$$

where w is the observed effect and a and b are arbitrary constants, and substituting for r in Eq. 2.1, the following expression may be derived:

$$\log\left(\frac{k}{a}\right) = w \log b + \frac{D}{\lambda} \log e + 2 \log D. \qquad (2.3)$$

Setting λ equal to 350 yd, a figure based, with appropriate correction for air density, on data of Scoville for Sandstone [8] and Storm for Ranger,[9] log b for a given shot may be evalu-

---

[5] L. H. Gray, "The Rate of Emission of Gamma Ray Energy by Radium B and Radium C, and Thorium B and Thorium C"," *Proceedings of the Royal Society London*, ACLIX, 263.

[6] G. R. White, "Penetration and Diffusion of Co[60] Gamma Rays in Water Using Spherical Geometry," *Physical Review*, LXXX (1950), 154.

[7] R. D. Evans, "Fundamentals of Radioactivity and its Instrumentation," *Advances in Biological and Medical Physics* (J. H. Lawrence and J. G. Hamilton, editors) (New York: Academic Press Inc., 1948).

[8] H. Scoville, Jr., E. J. Hoffman, and E. C. Vicars, "Gamma Radiation Versus Distance," Sandstone Report, Annex 8, Vol. 29.

[9] E. Storm, "Gamma Radiation as a Function of Distance, Operation Ranger," Los Alamos Scientific Laboratory Report LA–1228 (1951).

ated by the method of least squares using the field test data for w and D.

Conversely, the apparent mean free path of the gamma photons, λ, may be calculated using the data from the field and the relation between effect and dose for the control study. Assuming again that organ weight loss and dose follow the same relation in the field as in the control study, and with the knowledge that dose from a nuclear weapon is related to the square of the distance from the weapon for distances greater than 1,000 yd, it is possible to express the relation between dose and distance in the field as

$$\log (rD^2) = \alpha + \beta D \qquad (2.4)$$

where α and β are arbitrary constants. Substituting for log r from Eq. 2.2 in the above expression,

$$w \log b + \log a + 2 \log D = \alpha + \beta D, \qquad (2.5)$$

and by differentiating Eq. 2.5, with respect to D, β is given by

$$\beta = \log b \left(\frac{dW}{dD}\right) + \frac{2 \log_{10} e}{D}. \qquad (2.6)$$

The mean free path of the gamma photons is given by

$$\lambda = \frac{-\log e}{\beta}. \qquad (2.7)$$

It is assumed that the observed biological effect is directly proportional to the gamma-ray flux, and if no significant variation in the apparent gamma-ray spectrum of two weapons can be shown, the ratio of the kilotonnages of two weapons (i,j) can be calculated in the following manner. Assuming the gamma-ray flux at any point to be proportional to the kilotonnage, from Eq. 2.1, it is possible to write,

$$\frac{kt_i}{kt_j} = \frac{\dfrac{\sum\limits_{i=1}^{n_i}(r_i D_i^2 e^{D_i/\lambda})}{n_i}}{\dfrac{\sum\limits_{j=i}^{n_i}(r_j D_j^2 e^{D_j/\lambda})}{n_j}} \qquad (2.8)$$

and substituting for r from Eq. 2.2,

$$\frac{kt_i}{kt_j} = \frac{\sum_{i=1}^{n_i}(b_i^W D_{ie}^2 {}^{D_i/\lambda})}{\sum_{j=1}^{n_i}(b_j^W D_{je}^2 {}^{D_j/\lambda})} \qquad (2.9)$$

which is independent of a.

If the slopes of control and field experiments do not differ significantly and if figures for the mean free path of the gamma photons in each field experiment indicate a reasonable effective energy for the gamma radiation, the scaling of biological effects according to the estimates of yield calculated by Eq. 2.9 is considered justified. The scaling of the biological data to a nominal weapon of yield equal to that employed on Dog Shot and the con-

struction of a composite curve of biological effect for Dog, Easy, and George Shots is done in Chap. 6.

2.3 PLACEMENT OF EXPOSURE STATIONS

The placement of stations in Dog, Easy, and George Shots was based on predictions of gamma-ray flux vs distance presented in the Biomedical Handbook [10] and the Greenhouse Handbook.[11] The best estimates of weapon yield available during the planning phase of the experiments were used. Distances are presented in Tables 5.1 to 5.4.

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[10] W. H. Langham, R. E. Carter, J. T. Brennan, and P. S. Harris, "Handbook for Biomedical Experimenters, Operation Greenhouse," Los Alamos Scientific Laboratory Report LAB–J–675 (1950).

[11] "The Greenhouse Handbook of Nuclear Explosions," Scientific Director's Report of Atomic Weapons Tests at Eniwetok, 1951, Volume III (1951).

Chapter 3

Summary of Control Studies

From the control studies conducted with LAf$_1$ animals,[1] it was found that the relation between thymic weight loss and dose was adequately expressed by

(Female animals) $w = 0.1239$
$$+ 2.1557 \log r \pm 0.186 \qquad (3.1)$$

(Male animals) $w = 0.6025$
$$+ 1.8749 \log r \pm 0.242 \qquad (3.2)$$

---

[1] R. E. Carter *et al.*, "Change in Weight of Spleen and Thymus of the Mouse after Exposure to X Rays," Greenhouse Report, Annex 2.2, Part I.

where r is the dose of 230-KVP X radiation, w is the probit transformation of the per cent thymic weight loss, and 0.186 and 0.242 denote the estimated standard deviation from the regression (standard error of estimate). This relation was found to hold between 75 and 900 r. Equations 3.1 and 3.2 are plotted in Figs. 3.1 and 3.2. In the case of the spleen the best eye-fitted curve was drawn through the points and the dose corresponding to any per cent decrease in splenic weight was read from this curve. The curves for male and female animals are reproduced in Figs. 3.3 and 3.4.

Chapter 4

Experimental Method for Field Studies

4.1 DESCRIPTION OF APPARATUS

All mice exposed to gamma radiation on Dog and George Shots and half the mice exposed on Easy Shot were confined in hemispherical aluminum containers described in detail in the container report.[1] This container consisted of a cylindrical aluminum base buried in the ground with air intake and exhaust ducts. A plywood box separated incoming and exhaust air within the unit and confined heat generated by the ventilation fan motor to the exhaust portion of the unit (Figs. 4.1 and 4.2). Animals were confined in two rectangular lucite cages within the unit. Each cage measured 12 by 12 by 2 in. and was equipped with a galvanized-iron mesh top and bottom. Four tin watering boxes, holding 120 cc of water, were placed in each cage together with 150 g of food. On Dog and Easy Shots, 15 animals were placed in each cage. On George Shot 10 animals were placed in each cage. The position of the cages, shown in Fig. 4.3, was such that they were included completely within the aluminum hemisphere placed over the upper end of the aluminum base (Fig. 4.4). This placed the animals 15 to 18 in. above the mean ground level. A sloping mound of earth was brought up to the lower edge of the hemisphere. All exposure units had an unobstructed view of the weapon.

The wall thickness of the aluminum hemisphere was ¼ in. Measurements on the attenuation of radium gamma rays by the hemisphere wall were conducted in the field, using a 1-curie source 1 meter from the center of the hemisphere and 200-mr pocket ionization chambers to record dose in free air and within the hemisphere. These experiments indi-

cated that the dose at the center of the hemisphere was approximately 6 per cent lower than the free-air measurement.

The operating characteristics of the hemisphere units are described in the container report.[2]

Half the mice used for dosimetry on Easy Shot were placed in cylindrical exposure units together with mice used for median lethal-dose studies. Description of these units is included in the container report.

4.2 DESCRIPTION OF PROCEDURE

4.2.1 Selection of Animals

Animals used in the three shots were selected in the following manner. From the total number of animals available in the colony for the field tests, those animals whose ages fell between 7 and 9 weeks at test time were selected. From this population, male and female animals whose body weights fell between 20.0 and 23.9 g were used. For each shot the animals selected were divided into experimental groups of 20 or 30 each in a random manner with respect to age and weight.

The selection of animals for loading into exposure cages and exposure units was done according to tables of random numbers.

Both general and special control groups were kept for each shot. These animals were selected in a manner identical with the animals to be exposed to radiation. The general control animals never left the animal colony. The special control groups were placed in exposure units in the field on the rehearsal which preceded each weapon detonation. Their transportation to and from the shot is-

---

[1] R. H. Draeger, Greenhouse Report, Annex 2.3.

[2] *Ibid.*

land, and duration and conditions of confinement there corresponded almost exactly to the procedure for the actual shots themselves.

4.2.2 Placement and Recovery of Animals

Animals were transferred from animal colony cages to exposure cages 20 ± 2 hr prior to each shot. Food and water were placed in the cages at that time. Cages were transferred to cylinder liners [3] and transported by truck and landing ship to the shot islands, where the cages were placed in the exposure units and the aluminum hemisphere secured.

As soon as possible after shot time (6 ± 3 hr) animals were recovered from the exposure units and the cages replaced in cylinder liners for the return trip to the animal colony. Animals were returned to the animal-colony cages an average of 8 hr after shot time.

4.2.3 Splenic and Thymic Weight Determination

The weight of the spleen and thymus of each animal was determined 120 ± 3 hr after exposure according to the methods described in the control study.[4]

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[3] *Ibid.*

[4] R. E. Carter *et al.*, "Change in Weight of Spleen and Thymus of the Mouse after Exposure to X Rays," Greenhouse Report, Annex 2.2, Part I.

4.2.4 Statistical Analysis of Data

Data were analyzed according to the methods outlined in Appendix A. In the case of the spleen, the greatest percentage of weight loss observed in each experiment in the field was taken as 100 per cent and the remainder of the relative weight loss figures for the spleen for that shot adjusted accordingly, following the method used in the control study.[5]

Thirty animals were placed in each of the stations on Dog and Easy Shots, except in the case of Station 71d, Easy Shot, where 31 animals were used. Twenty animals were used in each of the stations on George Shot. The number of animals surviving to the 5th day after exposure is given in Tables 5.1 to 5.4. Inevitably occasional animals were lost or fatally injured during handling, accounting for the fact that in certain instances only 29 animals survived to the 5th day in stations where radiation deaths could not be expected. No animals or individual organs were excluded from the study, except where the organ weight decrease for any group fell outside the range observed in the control studies and predictions of the equivalent dose of 230-KVP X radiation received by the animals could not be made.

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[5] *Ibid.*

Chapter 5

Experimental Data from Field Studies

5.1 DOG SHOT

5.1.1 Organ Weight Changes at Varying Distances from Ground Zero

The organ weight changes at varying distances from ground zero for Dog Shot are presented in Table 5.1, together with the mean organ weights for the general and special control groups and the estimated equivalent dose of 230-KVP X radiation based on thymic and splenic response. National Bureau of Standards (NBS) film-badge exposure data at the various distances are also given. These film badges were located with the animals within the exposure units. The predicted dose for each station presented in Table 5.1 is based on gamma-ray curves from the Biomedical Handbook [1] and the Greenhouse Handbook. [2]

---

[1] W. H. Langham, R. E. Carter, J. T. Brennan, and P. S. Harris, "Handbook for Biomedical Experimenters, Operation Greenhouse," Los Alamos Scientific Laboratory Report LAB–J–675 (1950).

[2] "The Greenhouse Handbook of Nuclear Explosions," Scientific Director's Report of Atomic Weapon Tests at Eniwetok, 1951, Volume III (1951).

TABLE 5.1   ORGAN WEIGHTS AND NBS FILM-PACK DATA, DOG SHOT

STA-TION NO.	DISTANCE FROM GROUND ZERO (yd)	ANIMALS SURVIVING TO 5TH DAY	MEAN THYMIC WEIGHT (mg)	PER CENT DE-CREASE	MEAN SPLENIC WEIGHT (mg)	PER CENT DE-CREASE	PRE-DICTED[a] DOSE (140 kt) (r)	NBS FILM READ-INGS (r)	EQUIVALENT ROENTGENS 250-KVP X RAYS	
									Thymus	Spleen
. . .	General controls	60	67.1 ± 1.4 [b]	. . . .	77.5 ± 1.9 [b]	. . . . .				
. . .	Special controls	90	66.3 ± 1.4	. . . .	79.0 ± 1.7	. . . . .	. . . . .	. . .		
74a	1,550	29	5.4 ± 0.2	91.9	18.2 ± 0.4	100.0[c]	1,150	850[d] 895	815	>600
74b	1,575	30	6.2 ± 0.2	90.7	19.5 ± 0.4	97.8	960	810 810	751	>600
74c	1,635	30	9.6 ± 0.3	85.5	22.3 ± 0.3	93.2	730	673 687	565	>600
74d	1,670	30	10.9 ± 0.3	83.6	24.1 ± 0.4	90.3	555	607 607	518	570
74e	1,720	30	15.9 ± 0.4	76.1	29.6 ± 0.6	81.2	475	510 523	390	400
74f	1,775	30	23.3 ± 0.6	64.9	36.3 ± 1.2	70.2	365	386 332	275	305
74g	1,850	30	27.1 ± 0.6	59.1	56.9 ± 1.2	36.3	270	140 245	234	210
74h	2,100	30	42.9 ± 1.2	35.3	69.5 ± 1.2	15.3	210	108 119	122	150

(a) Based on Greenhouse Handbook figures.

(b) The mean is given together with its standard error.

(c) The maximum splenic weight loss observed was taken as 100 per cent, and the subsequent percentages were adjusted accordingly.

(d) Two film packs were included in each container.

The estimated yield used, 140 kt, was the best obtainable during planning phases of the experiment.

5.1.2 Estimate of Gamma-ray Dose as a Function of Distance from Ground Zero

Using Eq. 3.1 for the female mice in the control study, the doses of 230-KVP X radiation required to produce changes comparable to those observed at the various distances in the field were calculated. These data are presented in Fig. 5.1, where the log of roentgens of 230-KVP X radiation times the square of the distance from ground zero is plotted against distance from ground zero. A best line of fit to the points representing the thymus data was calculated and found to be

$$\log (rD^2 \times 10^{-7}) = 3.9197 - 0.001068D \pm 0.050 \quad (5.1)[3]$$

[3] The line log $(rD^2) = \alpha + \beta D$ (Eqs. 5.1, 5.2, 5.3, 5.4, 6.1, and 6.2) is presented with its estimated standard deviation from the regression $[S_{D \cdot \log (rD^2)}]$ which is dependent only on the scatter of the points $[\log (rD^2), D]$ about the line. The variance $[S^2_{D \cdot (rD^2)}]$ of this line cannot be combined directly with the variance $(S^2_{r \cdot \log r})$ of the control study regression since the two lines have correlated errors.

with the following statistical parameters

$$\bar{r} = -0.967 \qquad S_\alpha = 0.184 \qquad S_\beta = 0.000106.$$

Splenic data are included in Fig. 5.1 but were not used in the calculation of Eq. 5.1.

5.2 EASY SHOT

5.2.1 Organ Weight Changes at Varying Distances from Ground Zero

Organ weight changes, the mean organ weights for control groups, and the NBS film-pack exposure data for packs placed within the hemispherical animal containers are presented in Table 5.2. The estimated equivalent dose of 230-KVP X radiation based on thymic and splenic response is also given for each distance. Similar data for the cylinder animals are given in Table 5.3. The anticipated dose at each of the stations, estimated in the same manner as was used in Dog Shot, is presented in Tables 5.2 and 5.3. The predicted weapon yield was the best that could be obtained in the planning phase of the experiment.

TABLE 5.2 ORGAN WEIGHTS AND FILM-PACK DATA, EASY SHOT, HEMISPHERE STATIONS

STA-TION NO.	DISTANCE FROM GROUND ZERO (yd)	ANIMALS SURVIVING TO 5TH DAY	MEAN THYMIC WEIGHT (mg)	PER CENT DE-CREASE	MEAN SPLENIC WEIGHT (mg)	PER CENT DE-CREASE	PRE-DICTED[a] DOSE (50 kt) (r)	NBS FILM READ-INGS (r)	EQUIVALENT ROENTGENS OF 250-KVP X RAYS Thymus	Spleen
. . .	General controls	60	66.5±1.4[b]	. . . .	86.5±2.0[b]	. . . . .	. . . . .	. . . . .	. . . . .	. . . . .
. . .	Special controls	90	60.0±1.3[b]	. . . .	76.5±1.0	. . . . .	. . . . .	. . . . .	. . . . .	. . . . .
74a	1,260	0	. . . .	. . . .	. . . .	. . . . .	1,150	1,300	. . . . .	. . . . .
74b	1,300	13	4.1±0.2	93.2	14.8±1.0	100.0[c]	960	1,000	>900	>600
74c	1,360	30	5.9±0.2	90.2	18.8±0.5	93.7	730	820	729	>600
74d	1,420	30	9.3±0.3	84.5	23.5±0.3	86.0	555	635	542	500
74e	1,460	30	10.2±0.2	82.9	25.2±0.4	83.2	475	555	505	470
74f	1,520	29	14.7±0.5	75.4	29.2±0.5	76.7	365	460	381	350
74g	1,590	30	21.6±0.7	64.0	37.9±0.8	62.6	270	370	268	275
74h	1,650	29	23.3±0.4	61.1	50.3±1.0	42.6	210	290	249	220

[a] Based on Greenhouse Handbook figures.

[b] The mean is given together with its standard error.

[c] The maximum splenic weight loss observed was taken as 100 per cent, and the subsequent percentages were adjusted accordingly.

TABLE 5.3 ORGAN WEIGHTS AND FILM-PACK DATA, EASY SHOT, CYLINDER STATIONS

STA-TION NO.	DISTANCE FROM GROUND ZERO (yd)	ANIMALS SURVIVING TO 5TH DAY	MEAN THYMIC WEIGHT (mg)	PER CENT DE-CREASE	MEAN SPLENIC WEIGHT (mg)	PER CENT DE-CREASE	PRE-DICTED[a] DOSE (50 kt) (r)	NBS FILM READ-INGS (r)	EQUIVALENT ROENTGENS OF 230-KVP X RAYS	
									Thymus	Spleen
. . .	General controls	60	38.4±2.1[b]	. . . .	81.2±1.6[b]	. . . . .	. . . . .	. . .	. . .	. . .
. . .	Special controls	90	36.5±1.9	. . . .	73.8±1.3	. . . . .	. . . . .	. . .	. . .	. . .
70f	1,228	19	4.6±0.2	87.4	17.2±0.7	100.0[c]	850	760	>900	>600
70h	1,344	24	3.7±0.2	89.8	18.0±0.7	98.7	790	770	>900	>600
70m	1,384	28	4.6±0.2	87.3	19.8±0.5	95.5	655	680	899	>600
70t	1,440	29	7.7±0.3	78.9	20.9±0.4	93.5	520	570	593	>600
70v	1,490	29	9.3±0.6	74.5	22.0±0.7	91.7	410	455	498	575
71a	1,555	29	13.6±0.9	62.6	29.3±1.7	78.7	315	325	329	385
71d	1,650	31	15.5±0.9	57.5	38.9±1.4	61.8	210	220	280	330
71e	1,750	30	20.3±0.8	44.3	46.2±0.8	48.8	140	165	186	290

[a] Based on Greenhouse Handbook figures.

[b] The mean is given together with its standard error.

[c] The maximum splenic weight loss observed was taken as 100 per cent, and the subsequent percentages were adjusted accordingly.

5.2.2 Estimate of Gamma-ray Dose as a Function of Distance from Ground Zero

Using Eq. 3.1 for the female hemisphere animals and Eq. 3.2 for the male cylinder animals, the doses of 230-KVP X radiation required to produce changes comparable to those observed in the field were calculated. These data are presented in Fig. 5.2 for the hemisphere stations and in Fig. 5.3 for cylinder stations. A best line of fit to the points representing the thymus data was calculated and was found to be for the hemisphere stations,

$$\log (rD^2 \times 10^{-7}) = 3.6393 - 0.001114D \pm 0.026 \tag{5.2}[4]$$

with the following statistical parameters.

$$\bar{r} = -0.9781 \qquad S_\alpha = 0.150 \qquad S_\beta = 0.000106$$

and for the cylinder stations,

$$\log (rD^2 \times 10^{-7}) = 3.8655 - 0.001218D \pm 0.048 \tag{5.3}[5]$$

with the following statistical parameters.

$$\bar{r} = -0.9577 \qquad S_\alpha = 0.251 \qquad S_\beta = 0.000162.$$

[4] *Ibid.*

[5] *Ibid.*

Splenic data, included in Figs. 5.2 and 5.3, were not used in the calculation of Eqs. 5.2 and 5.3.

5.3 GEORGE SHOT

5.3.1 Organ Weight Changes at Varying Distances from Ground Zero

Organ weight changes, the mean organ weights for control groups, and NBS film-pack exposure data for packs placed within the animal containers are given in Table 5.4. The calculated equivalent dose of 230-KVP X radiation for the thymic and splenic response is also given for the various distances from ground zero. The anticipated dose at each of the stations, estimated in the same manner as was used in Dog Shot, is presented in Table 5.4. The predicted weapon yield was the best that could be obtained during planning phases of the experiment.

5.3.2 Estimate of Gamma-ray Dose as a Function of Distance from Ground Zero

Using Eq. 3.1 for the female mice in the control study, the doses of 230-KVP X radiation

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TABLE 5.4 ORGAN WEIGHTS AND FILM-PACK DATA, GEORGE SHOT

STA-TION NO.	DISTANCE FROM GROUND ZERO (yd)	ANIMALS SURVIVING TO 5TH DAY	MEAN THYMIC WEIGHT (mg)	PER CENT DE-CREASE	MEAN SPLENIC WEIGHT (mg)	PER CENT DE-CREASE	PRE-DICTED[a] DOSE (250 kt) (r)	NBS FILM READ-INGS (r)	EQUIVALENT ROENTGENS OF 230-KVP X RAYS	
									Thymus	Spleen
. . .	General controls	60	54.7±1.4[b]	. . . .	73.9±1.4[b]	. . . . .	. . . . .	. . .	. . .	. . .
. . .	Special controls	60	47.3±1.4	. . . .	74.5±1.8	. . . . .	. . . . .	. . .	. . .	. . .
74a	1,620	0	. . . .	. . . .	. . . .	. . . . .	1,330	4,300	. . .	. . .
74b	1,650	0	. . . .	. . . .	. . . .	. . . . .	1,050	[c]	. . .	. . .
74c	1,690	0	. . . .	. . . .	. . . .	. . . . .	920	3,000	. . .	. . .
74d	1,730	0	. . . .	. . . .	. . . .	. . . . .	780	2,600	. . .	. . .
74e	1,775	0	. . . .	. . . .	. . . .	. . . . .	650	2,000	. . .	. . .
74f	1,830	0	. . . .	. . . .	. . . .	. . . . .	540	1,600	. . .	. . .
74g	1,910	17	4.2±0.2	89.4	18.5±0.6	100.0[d]	400	[c]	694	>600
74h	2,160	20	29.3±1.0	61.9	34.2±1.1	72.0	230	460	253	315

[a] Based on Greenhouse Handbook figures.

[b] The mean is given together with its standard error.

[c] NBS film packs at these stations were lost during the development and reading process.

[d] The maximum splenic weight loss observed was taken as 100 per cent, and the subsequent percentages were adjusted accordingly.

required to produce changes comparable to those observed at the various distances in the field were calculated. These data are presented in Fig. 5.4, where the log of roentgens of 230-KVP X radiation times the square of the distance from ground zero is plotted against the distance from ground through the two points given in Eq. 5.4.

$$\log (rD^2 \times 10^{-7}) = 4.9375 - 0.001327D . \tag{5.4}$$

Splenic data for George Shot are included in Fig. 5.4.

Chapter 6

The Relative Biological Effectiveness of Initial Gamma Radiation from an Atomic Weapon

The values of the slopes of the regression lines for the field experiments, determined by the methods outlined in Sec. 2.2 are given in Table 6.1, together with the comparable figures for the control studies.

Also included in Table 6.1 are the values for the apparent mean free path of the gamma photons, calculated according to the method outlined in Sec. 2.2, and the estimates of the yield of the weapons used on each shot, calculated from the biological data by the method given in Sec. 2.2. In these calculations, the Dog Shot yield, taken as the point of reference, was assumed to be 92 kt.

Since significant differences in the slopes of field-study curves and control-study curves could not be demonstrated, and in view of the substantial agreement between calculated values for the mean free path of the gamma photons and existing theory, it was felt that combination of the data of all shots in the following manner was justified. All data from the three shots were normalized to the estimated yield of Dog Shot using the values for yields calculated from Eq. 2.9 and presented in Table 6.1. These normalized data are presented in Fig. 6.1, where r, the equivalent dose of 230-KVP X radiation times the square of the distance from ground zero, is plotted against distance from ground zero. The equation for the best line of fit to the thymic data is

$$\log\ (rD^2 \times 10^{-7}) = 4.1310 - 0.00119D \pm 0.041, \tag{6.1}$$

with the following statistical parameters:

$$\bar{r} = -0.9952 \qquad S_\alpha = 0.078 \qquad S_\beta = 0.000046.$$

The points representing splenic data were not used in the calculation of Eq. 6.1.

The best line of fit to the NBS film-pack data presented in Tables 5.1, 5.2, and 5.4 and normalized to 92 kt according to the estimates of yield given in Table 6.1, was found to be

$$\log\ (rD^2 \times 10^{-7}) = 4.1030 - 0.00113D \pm 0.065, \tag{6.2}$$

where 0.065 denotes the standard deviation from the regression (standard error of estimate), and with the following statistical parameters:

$$\bar{r} = 0.973 \qquad S_\alpha = 0.108 \qquad S_\beta = 0.000066.$$

The lack of significant difference between the β constants of Eqs. 6.1 and 6.2 made a determination of the relative biological effectiveness of radiation and bomb gamma radiation possible through comparison of the α constants. The relative biological effectiveness of initial gamma radiation from an atomic bomb and 230-KVP X radiation was found to be 0.94.

TABLE 6.1 THE SLOPES OF FIELD-STUDY REGRESSION LINES, THE MEAN
FREE PATH OF GAMMA RADIATION, AND THE YIELD OF THE
WEAPONS USING BIOLOGICAL AND FILM DATA

EXPERIMENT	RECIPROCAL OF REGRESSION COEFFICIENT (1/log b)	MEAN FREE PATH OF GAMMA RADIATION (yd)	WEAPON YIELDS, BIOLOGICAL DATA[a] (kt)	WEAPON YIELDS, NBS FILM DATA[a] (kt)
Control study (female animals)	2.156±0.056[b]	. . .	. . .	. . .
Control study (male animals)	1.875±0.068	. . .	. . .	. . .
Dog Shot (female animals)	1.895±0.136	407	92	92
Easy Shot hemispheres (female animals)	1.944±0.226	390	37	41
Easy Shot cylinders (male animals)	1.814±0.159	357	47	35
George Shot (female animals)	2,225	327	320	472

[a] Dog Shot is assumed to be 92 kt.
[b] The reciprocal of log b is given together with its standard deviation.

Chapter 7

Discussion

The lack of significant variation between the slopes of the control and field experiments, together with the values found for the mean free path of the gamma photons in each field test, was felt to justify the scaling of biological data for the three detonations according to the ratios of the weapon yields found by the method presented in Sec. 2.2. The resultant composite curve (Eq. 6.1) is the expression of the biological effectiveness of the initial gamma radiation from an atomic explosion, in terms of biologically equivalent roentgens of 230-KVP X radiation, at varying distances from an atomic weapon of yield equal to that employed in Dog Shot.

A comparison of the composite curve for the biological data from hemisphere stations and a composite curve for film-badge data prepared in an identical manner (Eq. 6.2) indicated a ratio of biological effectiveness of essentially unity (0.94) between initial gamma radiation from an atomic weapon as registered by film badges, and 230-KVP X radiation as registered by the thymic weight decrease. No statistically significant difference between the constants of Eqs. 6.1 and 6.2 could be demonstrated. It is noted, however, that in all but two instances, the biological estimate of dose fell below the film-badge readings.

The apparent ratio of biological effectiveness given is dependent on film-badge readings and hence on the calibration of the film badges for the gamma-ray energies encountered. It can be considered accurate in so far as the radiation spectra used for film-badge calibration resembled the actual gamma-ray spectrum encountered in the field.

At the time of writing discrepancies appear between the biological estimates of weapon yield and physical estimates. Using Dog Shot as the point of reference, biological results indicate that the Easy Shot yield was lower than that predicted by other methods, while George Shot yield was higher. The variation in Easy Shot yield cannot be explained at the present time. The possibility of neutrons contributing to the greater biological effect seen on George Shot as compared with initial predictions seems remote. Rather it would seem likely that conventional gamma-intensity scaling laws may not hold for the larger sized weapons or for weapons of different assembly.

From the composite curve of biological data, using Eq. 2.7, the mean free path of the gamma photons was found to be 366 yd.

Mice placed in cylindrical containers on Easy Shot showed a consistently greater effect than mice placed in hemispherical containers at the same distances. Film-badge readings for cylindrical containers were lower than values for hemispherical containers, indicating possible variations in dosage throughout the cylindrical container.

With the strain of mice used for these experiments, the variation in organ weights of any one group of animals was small compared with the variation between groups. Where, in possible future use of the biological indicator, such a situation is found to exist, the size of each individual group of animals could be reduced substantially without altering the uncertainty of the best line of fit to the data obtained from any one experiment. With the uncertainty of yield of atomic weapons, the use of a larger number of stations on each shot would have circumvented the considerable loss of biological data on such tests as George Shot.

Chapter 8

Summary

The following is a summary of the results of this experiment:

(1) Change in the weight of the thymus of the LAf$_1$ mouse under field conditions proved satisfactory as a biological indicator of radiation damage using relatively small numbers of animals and few stations.

(2) The biological effect of initial gamma radiation from an atomic explosion, expressed in terms of roentgens of 230-KVP X radiation, was found to be

$$\log\,(rD^2 \times 10^{-7}) = 4.1310 - 0.00119D \pm 0.041 \tag{8.1}$$

where D is the distance from ground zero in yards and the weapon yield is assumed to be 92 kt.

(3) The ratio of biological effectiveness of 230-KVP X radiation and initial gamma radiation from an atomic weapon was found to be unity within the uncertainty of biological and film-badge data. This ratio is dependent on the calibration of the film badges and is singular to the Greenhouse tests in as far as the estimates of absolute gamma dose from film-badge readings are singular to the particular tests in question.

(4) Composite biological data for all tests indicated a mean free path for gamma photons of 366 yd.

Appendix A

Statistical Methods

The following equations were those used to estimate the population parameters presented in the report:

mean:

$$\frac{\sum\limits_{i=1}^{n} x_i}{n} = \bar{x},$$

where x_i is the data and n the number of data;

variance:

$$\frac{\sum\limits_{i=1}^{n}(x_i-\bar{x})^2}{n-1} = S_x^2;$$

standard deviation:

$$\sqrt{S_x^2} = S_x;$$

standard error of the mean:

$$\frac{S_x}{\sqrt{n}}.$$

A regression line, $\hat{y} = bx + a$, is fitted to data (x_i, y_i) as follows:

in matrix notation, $AB = G$,

where $A =$

$$\begin{pmatrix} \sum w_i & \sum w_i x_i \\ \sum w_i x_i & \sum w_i x_i^2 \end{pmatrix}, \quad B = \begin{pmatrix} a \\ b \end{pmatrix}, \quad G = \begin{pmatrix} \sum w_i y_i \\ \sum w_i x_i y_i \end{pmatrix}$$

and where w_i indicates weight of y_i.

Then $B = A^{-1}G$, where a and b are the parameters in a least-square line which minimizes deviations from y_i.

The estimate of the variance of points (x_i, y_i) from the regression is given by:

$$S_{y \cdot x}^2 = \sum_{i=1}^{n} \frac{w_i(y_i - \hat{y}_i)^2}{n-2} = \frac{1}{n-2}\left[\sum_{i=1}^{n} w_i y_i^2 - B^T G\right]$$

where B^T is the transpose of B.

$S_{y \cdot x}$ is the estimated standard deviation from the regression (standard error of estimate).

The variance and covariance of the coefficients a and b are estimated by:

$$V(a) = S_{y \cdot x}^2 C_{11}$$
$$V(b) = S_{y \cdot x}^2 C_{22}$$
$$\text{Cov}(a,b) = S_{y \cdot x}^2 C_{12},$$

where C_{ij} are the elements of the inverse matrix A^{-1}. The estimated standard deviations are then:

$$\sqrt{V(a)} = S_a \text{ and } \sqrt{V(b)} = S_b.$$

The estimated product moment coefficient of correlation is given by:

$$r_{x \cdot y} = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}},$$

which may be corrected for sample size as follows:

$$\bar{r}_{x \cdot y} = \sqrt{\frac{1 - (1 - r_{x \cdot y}^2)(n-1)}{(n-2)}}.$$
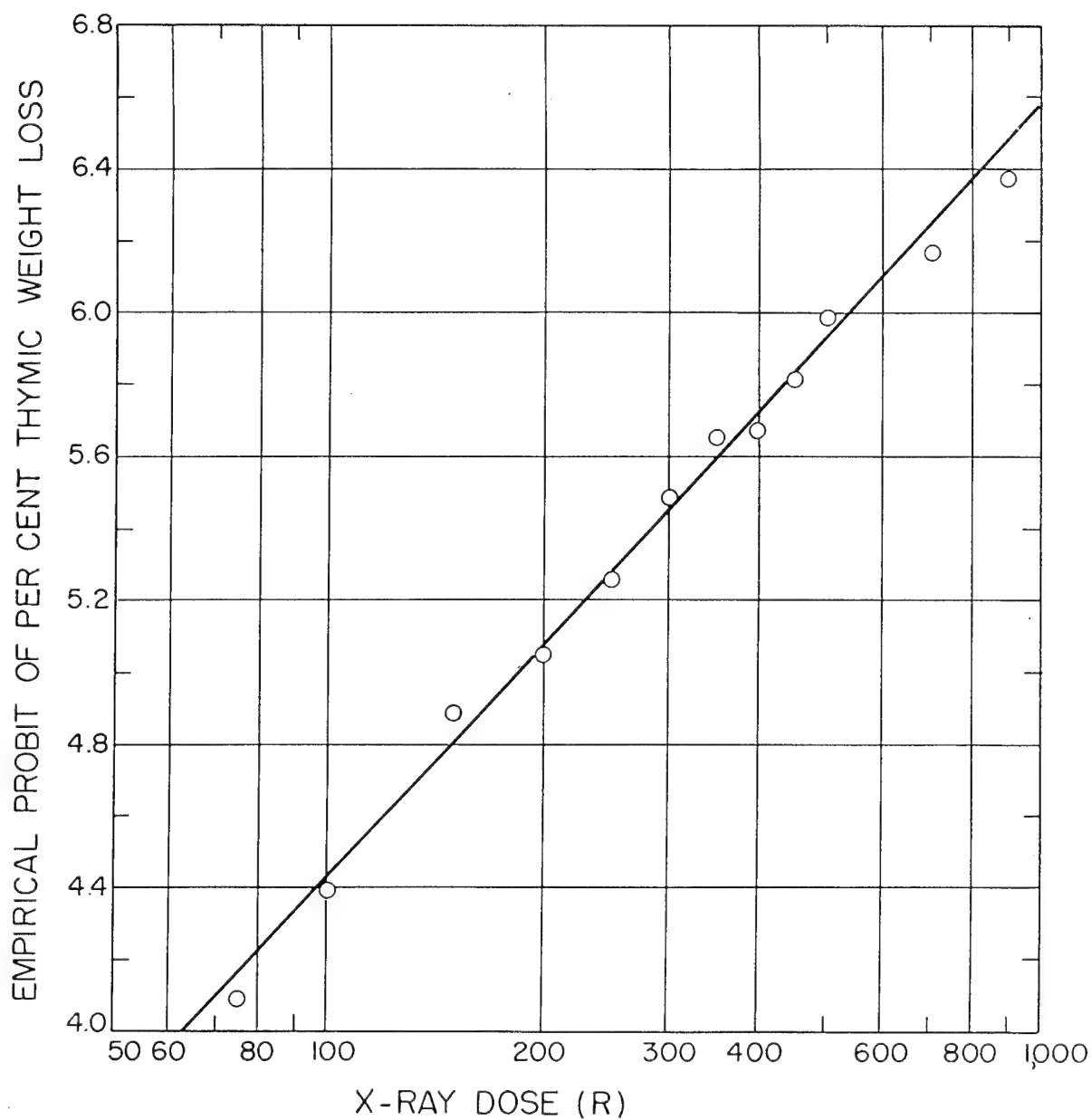
Fig. 3.1 Effect of X Radiation on the Weight of the Thymus of LAf₁ Female Mice
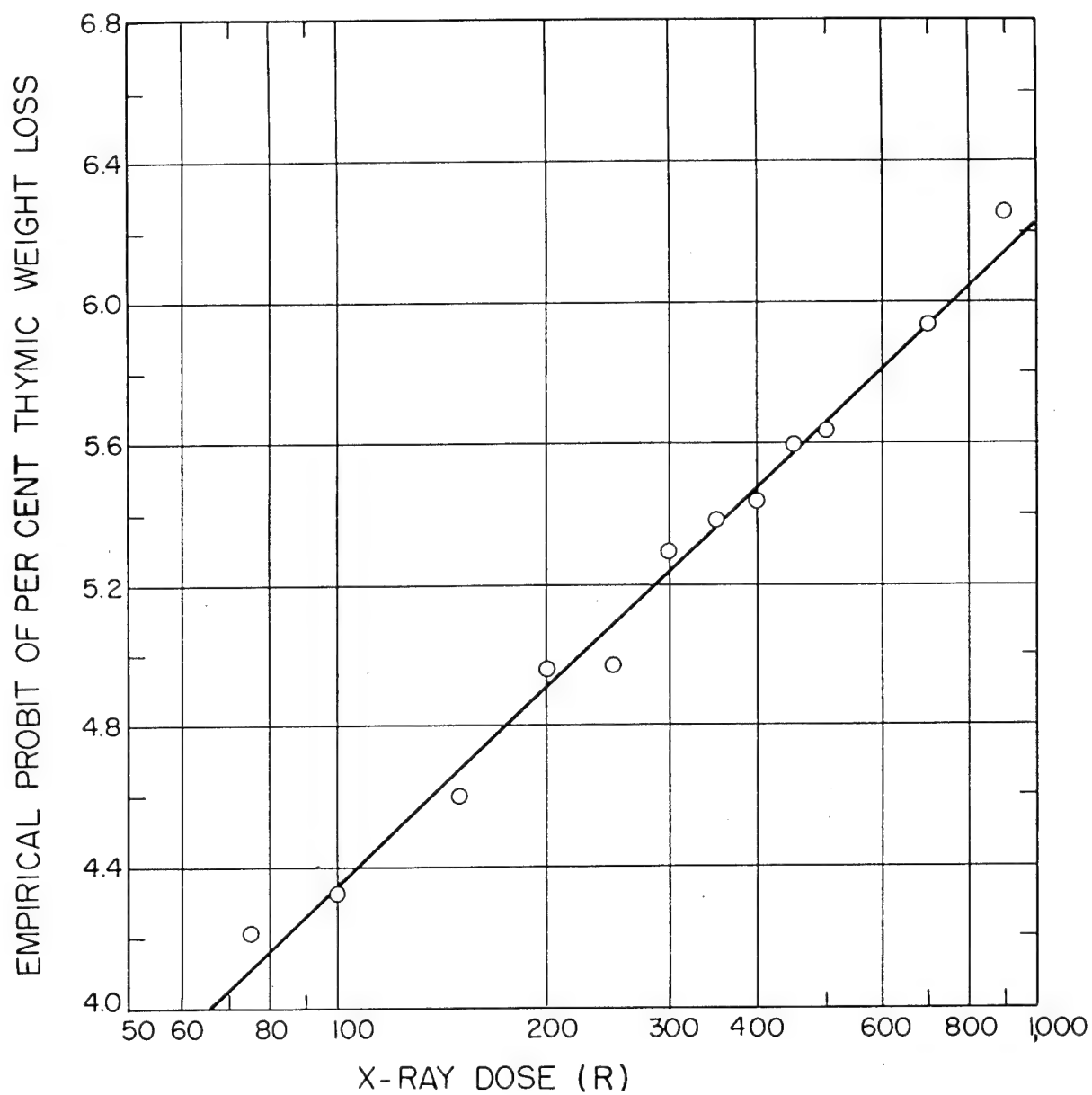
Fɪɢ. 3.2   Effect of X Radiation on the Weight of the Thymus of LAf₁ Male Mice
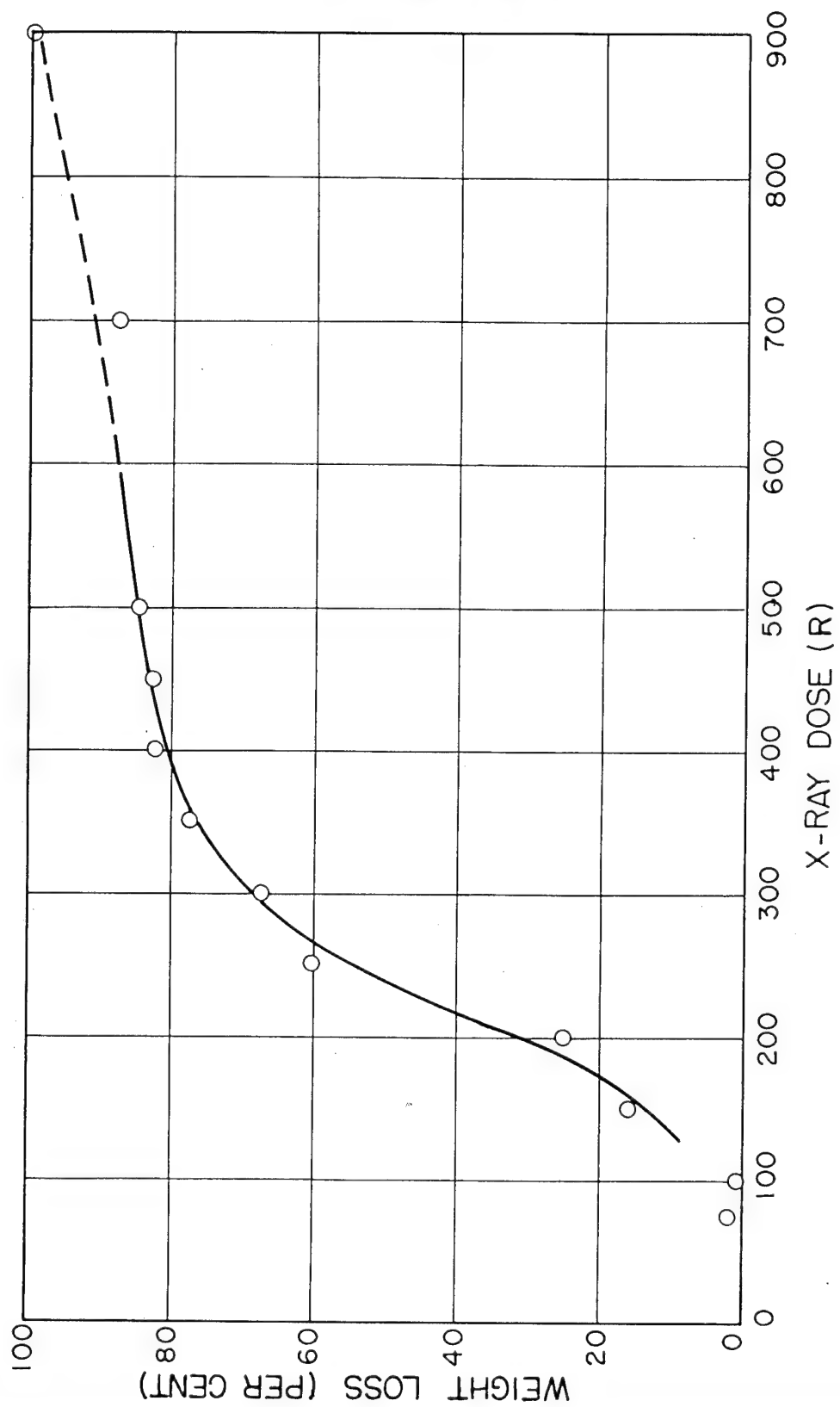
Fig. 3.3 Effect of X Radiation on the Weight of the Spleen of LAf, Female Mice
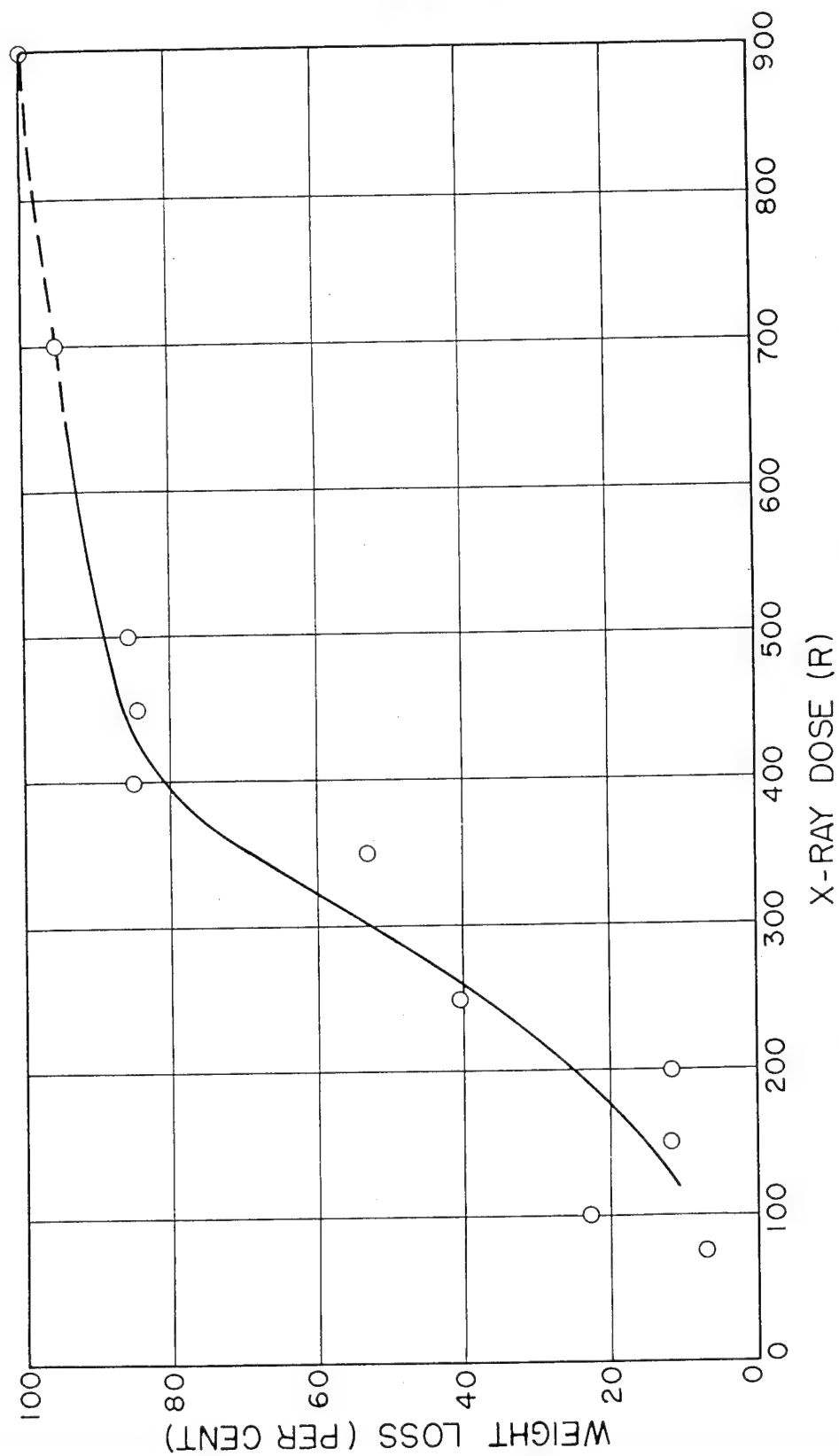
Fig. 3.4 Effect of X Radiation on the Weight of the Spleen of LAf, Male Mice

FIG. 4.1 Hemispherical Animal Container Showing Base, Exhaust and Intake Air Ducts, and Box Housing Blower Fan

Fig. 4.2 Hemispherical Animal Container Showing Base with Air Ducts and Blower-motor Housing in Place

Fig. 4.3   Hemispherical Animal Container Showing Animal Cages in Place above Blower-motor Housing

FIG. 4.4 Hemispherical Animal Container with Aluminum Hemisphere in Place Ready for Use
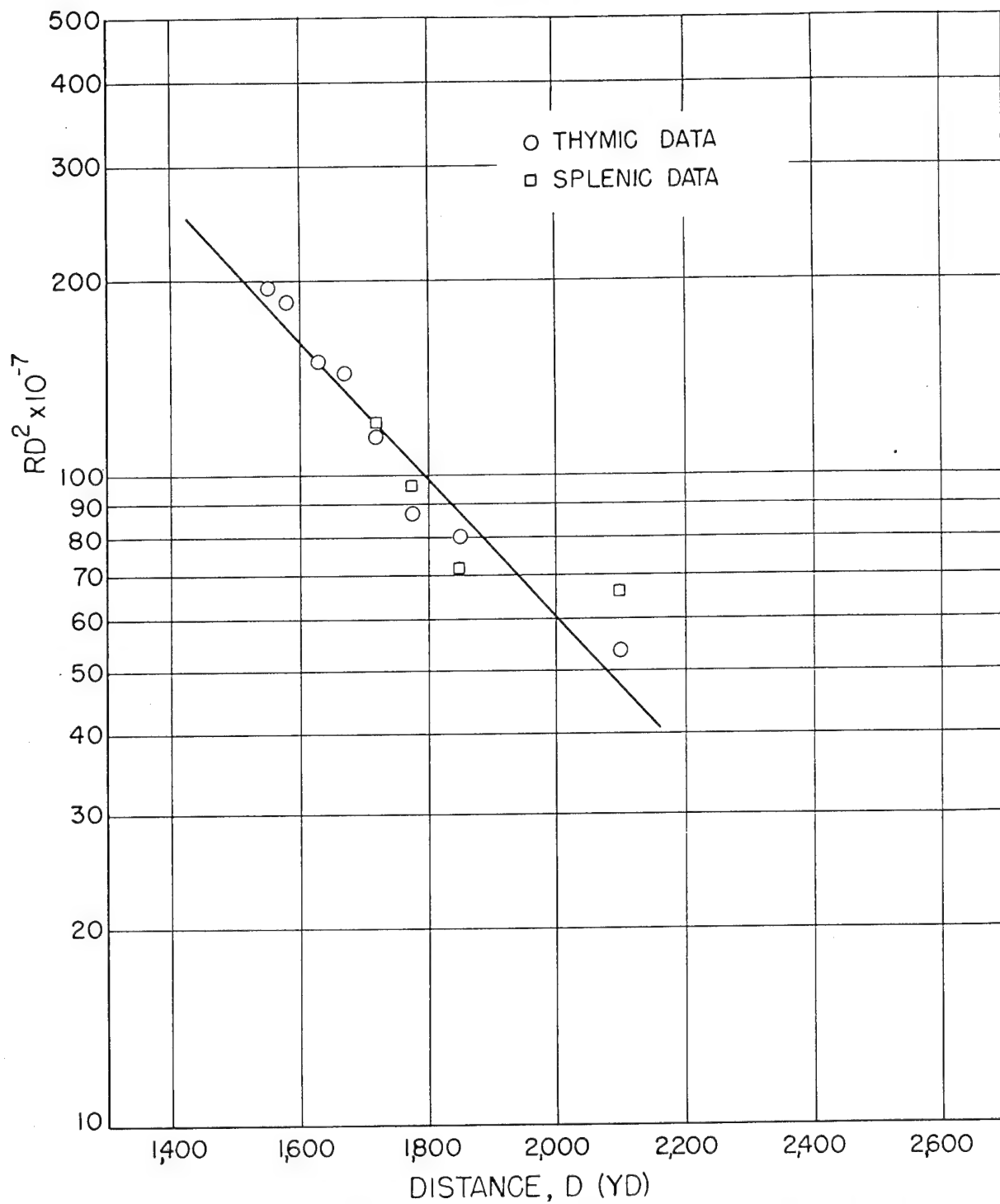
FIG. 5.1 Dog Shot, Biological Effectiveness of Initial Gamma Radiation in Terms of Equivalent Roentgens of 230-KVP X Radiation (r) at Varying Distances from Ground Zero
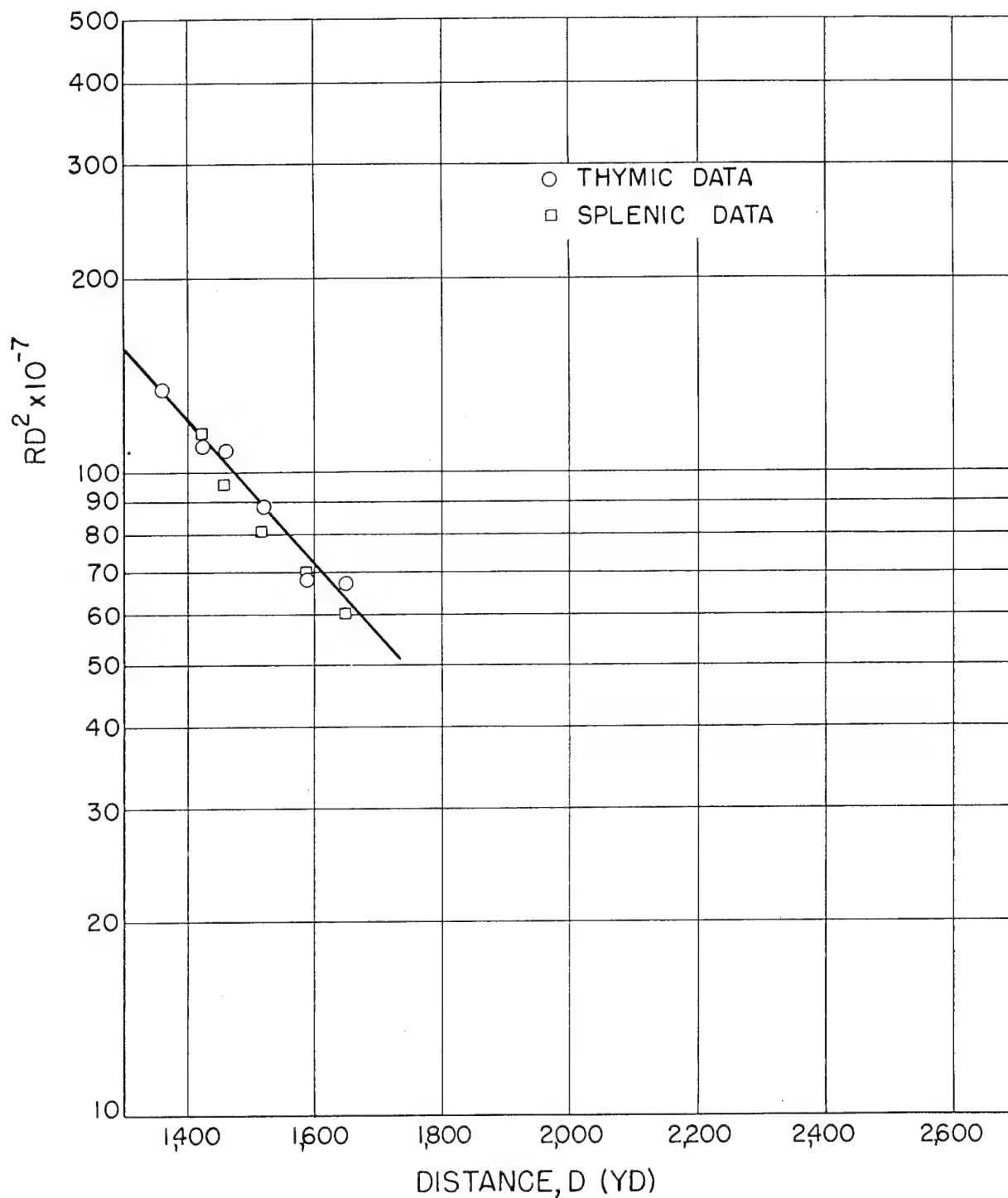
Fig. 5.2 Easy Shot Hemisphere Stations, Biological Effectiveness of Initial Gamma Radiation in Terms of Equivalent Roentgens of 230-KVP X Radiation (r) at Varying Distances from Ground Zero
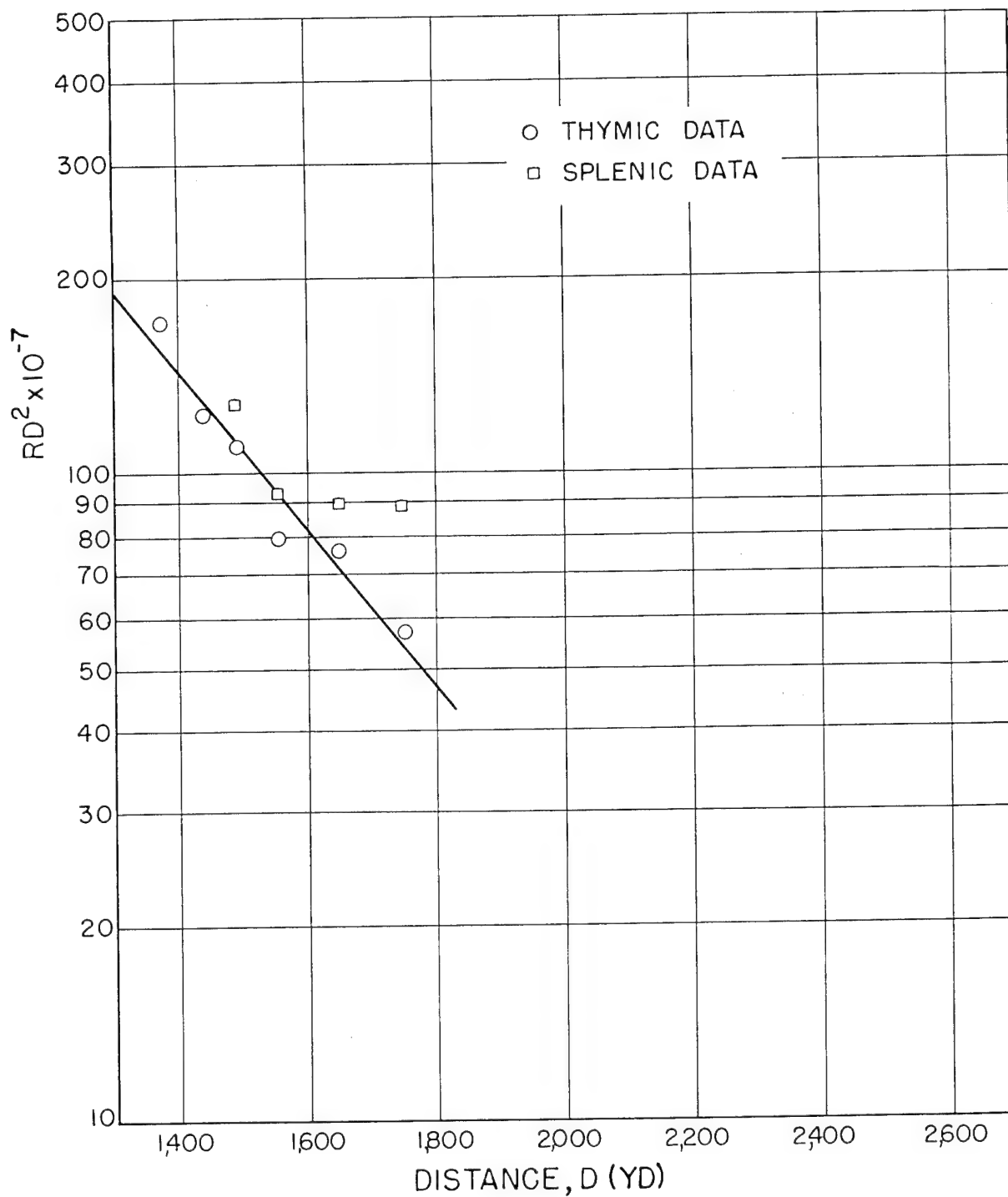
FIG. 5.3 Easy Shot Cylinder Stations, Biological Effectiveness of Initial Gamma Radiation in Terms of Equivalent Roentgens of 230-KVP X Radiation (r) at Varying Distances from Ground Zero
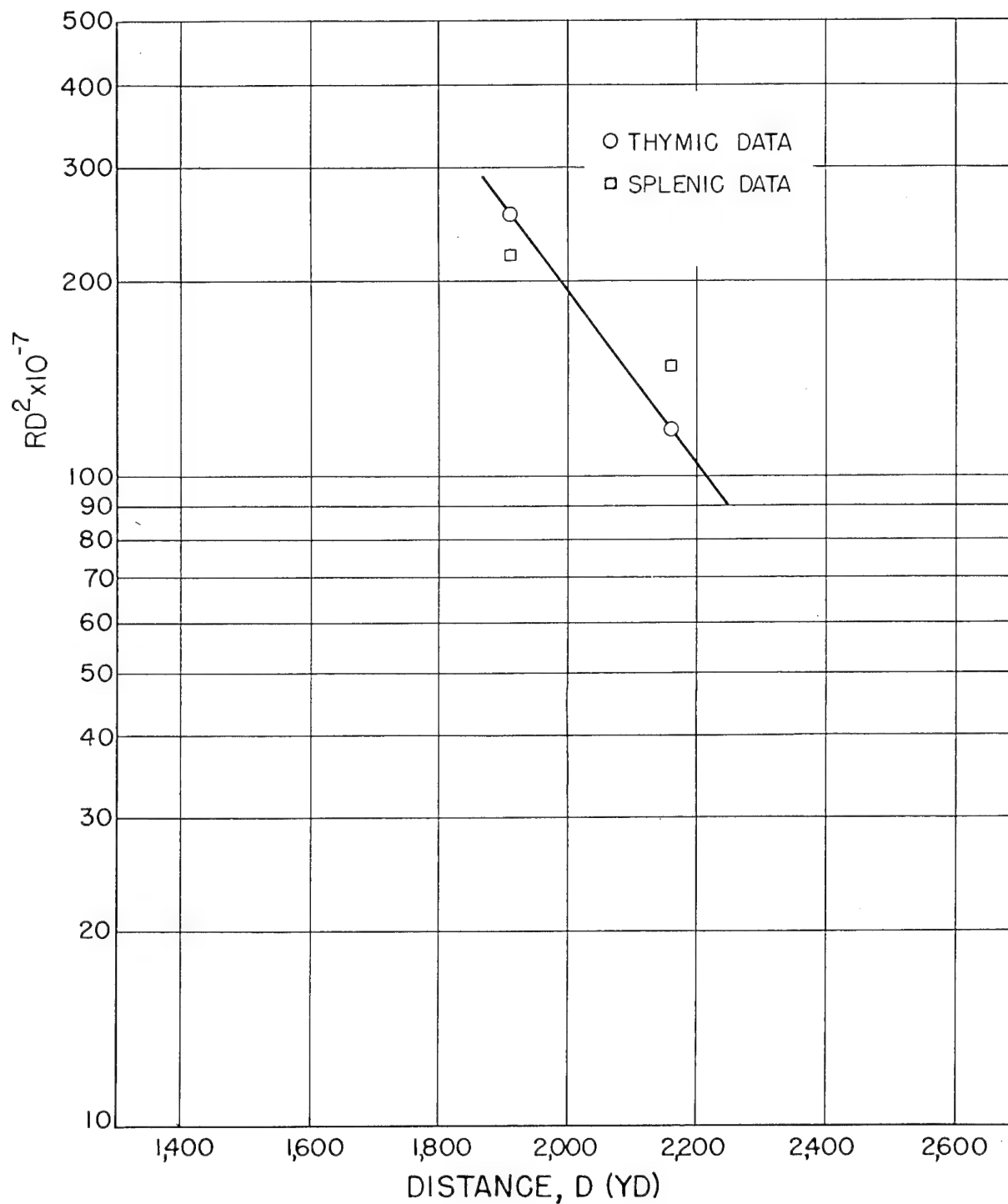
FIG. 5.4 George Shot, Biological Effectiveness of Initial Gamma Radiation in Terms of Equivalent Roentgens of 230-KVP X Radiation (r) at Varying Distances from Ground Zero
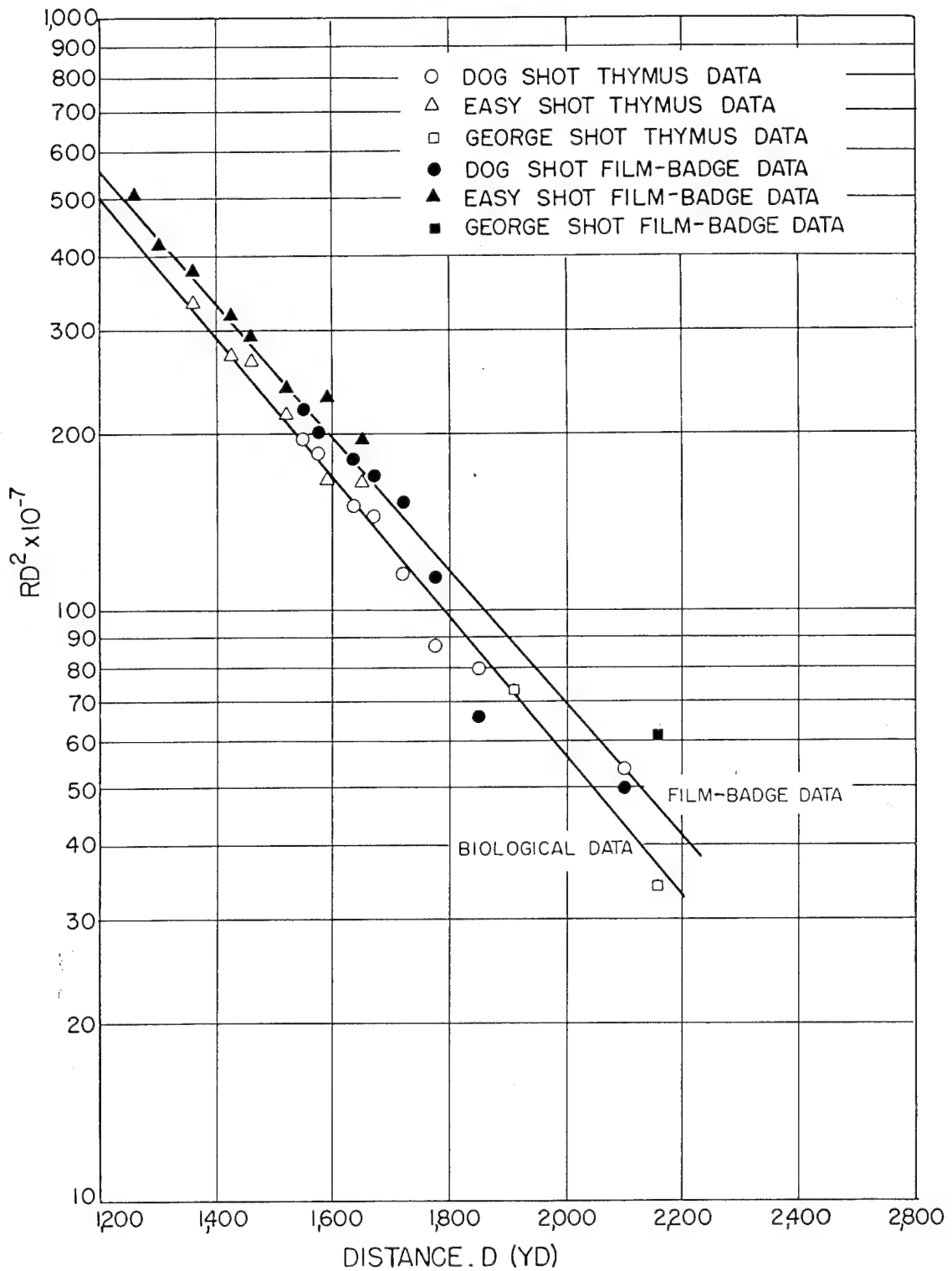
FIG. 6.1 Biological Effectiveness of Initial Gamma Radiation in Terms of Equivalent Roentgens of 230-KVP X Radiation (r) at Varying Distances from Ground Zero (hemisphere stations for Dog, Easy, and George Shots scaled to a nominal Dog Shot weapon according to biological estimates of yield)

Section 2

THE BIOLOGICAL EFFECTIVENESS OF NEUTRON RADIATION FROM AN ATOMIC BOMB

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Acknowledgments

Abstract

During Operation Greenhouse LAf$_1$ mice were exposed to the neutron radiation from Dog, Easy, and George Shots. The animals were protected from bomb blast, thermal radiation, and gamma rays by confinement in hemispherical lead shields 7 in. thick. The integrated biological effects of total bomb neutron flux was measured successfully by comparing the weight decrease of the mouse spleen and thymus produced by bomb neutrons with that produced by 230-KVP X rays. Over the range studied the integrated neutron dose from Dog and George Shots varied with distance from zero according to the following expressions:

Dog Shot, log rem $= 9.59497 - 1.00393 \times 10^{-2}D + 3.27616 \times 10^{-6}D^2$,

George Shot, log rem $= 4.98220 - 6.61359 \times 10^{-4}D - 8.31286 \times 10^{-7}D^2$.

On Easy Shot results were obtained at only one distance because of its greater neutron flux per kiloton.

Theoretical considerations indicate that the lead shield provided adequate protection from bomb gamma rays and was effectively transparent to the neutrons although there was some degradation of neutron energies. The results showed that slow neutrons contributed a negligible fraction of the total neutron effect. Ninety per cent or more of the biological effect from each bomb was produced by neutrons with energies of 1 Mev or greater. For Dog and Easy Shots 50 to 75 per cent of the neutron dose was produced by neutrons of intermediate energies. For George Shot over 80 per cent of the neutron effect was due to neutrons of 3 Mev or greater. The ratio of gamma to neutron dose at 1,000 yd from the detonation varied with the weapon assembly. The total biological effect of neutrons was approximately 1.5, 3 to 4 and 11.4 per cent of the gamma dose over the range studied for George, Dog, and Easy Shots, respectively. At the present time the lack of physical measurements of flux and spectrum of neutrons between 0.4 ev and 3 Mev makes a biological technique the most reliable method of estimating the integrated biological effect of the total neutron flux from an atomic explosion.

Chapter 1

Introduction

1.1 PURPOSE AND JUSTIFICATION OF THE EXPERIMENT

Current military and civil defense planning assumes that neutrons from an atomic explosion represent a negligible radiation hazard as compared with that due to gamma rays.[1] The above assumption is based on theoretical considerations and on measurement of apparent neutron spectrum and flux using gold and sulfur threshold detectors. There is obviously, a very large energy range from about 0.4 ev to 3 Mev, for which no physical and biological experimental information is available.[2]

Prior to the present experiment it was anticipated, but not established, that the biological effects of bomb neutrons were due chiefly to neutrons of intermediate energies. The lack of physical and biological data regarding the flux and spectrum of bomb neutrons of intermediate energy is ample reason for using a biological system to measure their biological effect directly. The biological test system used in this experiment integrates the over-all biological effect of neutron radiation and gives a result in terms of rem (footnote 3). This information may be obtained independently of any physical measurements of flux or energy spectrum.

The present experiment was therefore included in the Biomedical program of Operation Greenhouse to measure directly the integrated biological effect of the total neutron flux from an atomic explosion as a function of distance from the detonation.

The present state of physical and biological knowledge does not permit the measurement of the biological effectiveness of bomb neutrons in terms of total ergs of energy absorbed. It is not possible, therefore, to measure the true relative biological effectiveness (RBE)[4] of bomb neutrons. It is quite feasible however to measure, in rem, the integrated biological effect of an unknown flux of neutrons of unknown spectrum.

1.2 SUMMARY OF PREVIOUS COMPARABLE EXPERIMENTS

No previous biological experiments on bomb neutrons have been attempted. All previous concepts of the biological effects of bomb neutrons have been derived from physical data.

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[1] Armed Forces Special Weapons Project, *Radiological Defense*, II (1951), 3.57.

[2] *The Effects of Atomic Weapons*, p 244 (Los Alamos Scientific Laboratory and U. S. Government Printing Office, Washington, D. C., 1950).

[3] One rem is that dose of any ionizing radiation which produces a relevant biological effect equal to that produced by 1 r of high-voltage X radiation, other exposure conditions being equal.

[4] True RBE=rem/rep and necessitates a knowledge of energy spectrum and flux.

Chapter 2

Physical Characteristics of Bomb Neutrons

2.1 ORIGIN, SPECTRUM, AND FLUX

Neutrons emanating from an atomic explosion fall into three categories:

(a) Prompt neutrons: those produced within 10^{-8} sec after fission.

(b) Delayed neutrons: those produced by the decay of fission products within the first minute after fission.

(c) Photo neutrons: those produced by (γ,n) reactions.

The ratio of the production of prompt neutrons to delayed neutrons is about 100 to 1. Many of the prompt neutrons are absorbed, however, in the bomb assembly before it is blown apart; consequently, the ratio of prompt to delayed neutrons which escape the bomb is only about 20 to 1. The photo-neutrons are a negligible fraction of the total neutron flux.

It may be deduced that after traveling several mean free paths in air, bomb neutrons will consist of radially divergent beams of unscattered fast neutrons followed by expanding cones of singly or multiply scattered neutrons of lower energy. The first neutrons to arrive at any point will be high-energy neutrons. Afterward come lower energy neutrons which rapidly shift the neutron spectrum to the low-energy side.[1] Since the present experiment was designed to integrate the effects of all neutrons, spectrum vs time data were not needed. However, spectrum vs distance data could have been used if they had been available.

2.2 PHYSICAL MEASUREMENT OF BOMB NEUTRON FLUX

In all field tests, including Operation Greenhouse, bomb neutron fluxes were measured by observing the induced activity in two kinds of detectors. Gold foils were used to measure the flux of slow neutrons in the energy range 0 to 0.4 ev. The foils were exposed in pairs, one covered with cadmium, the other not. Neutron flux was evaluated by employing the cadmium difference technique. Powdered sulfur samples were utilized to measure the flux of neutrons having energies of 3 Mev and greater. The basis of this latter measurement is the reaction $S^{32}(n,p)P^{32}$ which has a rather sharp threshold near 3 Mev. It is important to note that no physical measurements of any kind are available concerning bomb neutron flux in the very large intermediate energy range 0.4 ev to 3 Mev. All that is known about the neutron flux in this energy range is inferred from the measurements made with gold and sulfur samples.

In this report the three classes of bomb neutrons mentioned above will be referred to as "gold neutrons" (0 to 0.4 ev), "intermediate neutrons" (0.4 ev to 3 Mev), and "sulfur neutrons" (>3 Mev).

Neutron flux measurements at Operations Sandstone and Ranger [2,3] showed that the curves representing gold neutron flux vs distance, and sulfur neutron flux vs distance, were nearly parallel and the ratio of total gold

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[1] Sandstone Report, Annex 8, Vol. 29, F. Shonka and G. Pawlicki, "Report of LAJ-5 on Gamma Measurements."

[2] *The Effects of Atomic Weapons* (Los Alamos Scientific Laboratory and U. S. Government Printing Office, Washington, D. C., 1950).

[3] Operation Ranger, unpublished data.

neutrons to total sulfur neutrons was about 10 to 1. Another important conclusion derived from these data is that the bomb neutron flux is not simply proportional to bomb kilotonnage. To a considerable extent neutron flux depends upon the details of bomb assembly.

Chapter 3

Biological Measurements of Radiation Effects

3.1 SPLENIC AND THYMIC WEIGHT LOSS IN MICE AS A QUANTITATIVE BIOLOGICAL INDICATOR OF RADIATION DAMAGE

Reduction in weight of the spleen and thymus of the mouse following ionizing irradiation has been recognized for many years.[1] Previous experiments have shown that a high degree of correlation exists between reduction in splenic and thymic weight of the mouse and the dose of X radiation given the animal.[2,3] In the case of the thymus, this weight loss is believed to consist almost entirely in a loss of lymphocytes, while in the case of the spleen, lymphocyte loss is considered the principal factor for doses up to 400 r for LAf₁ mice.[4] In the pre-operational control studies [5,6] the spleen-thymus method was tested using a wide variety of X rays (ranging from 230-KVP to 22-Mev betatron X rays) as well as the mixed gamma rays and slow neutrons in the thermal column of the Los Alamos homogeneous reactor. In all cases the spleen-thymus response varied quantitatively with radiation dose. For this reason the spleen-thymus response is an adequate biological indicator for

assessing the biological effectiveness of bomb neutron radiation.

3.2 METHOD OF MEASURING BIOLOGICAL EFFECTS OF RADIATION BY MOUSE SPLEEN-THYMUS WEIGHT DECREASE

Extensive pre-test control studies [7,8] showed that the per cent decrease in the weight of the spleen and thymus of the mouse following exposure to ionizing radiation varied with the radiation dose according to the relation

$$\text{Log } Y = a + bX$$

where Y is the radiation dose in roentgens or rep and X is the per cent organ weight loss. To determine the dose in rem of an unknown radiation exposure it is necessary to first establish the constants a and b in the above expression by means of an adequate control experiment in which the organ weight loss is measured following exposure of animals to graded doses of high-energy X rays. A control experiment is carried out by selecting several groups of 20 to 30 animals each from the test population. The animals are selected and assigned to exposure groups on a strictly random basis. The groups are exposed to graded doses of 230-KVP X rays, ranging from 100 to 900 r. One group of animals is kept as an unirradiated control. Five days after exposure the animals are sacrificed and the spleens and thymuses dissected out and weighed. The mean percentage organ weight decrease for the irradiated groups is determined from the mean organ weights of the un-

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[1] H. Heineke, "Ueber die Einwekung der Röntgenstrahlen auf innere Organs," *Munchener medizinische Wochenschrift,* LI (1904), 785.

[2] R. E. Carter, P. S. Harris, and J. T. Brennan, "The Effect of Acute Doses of X Irradiation on the Splenic and Thymic Weight of CF1 Female Mice," Los Alamos Scientific Laboratory Report LA–1075 (1950).

[3] J. T. Brennan *et al.,* "Change in the Weight of Spleen and Thymus of the Mouse after Exposure in a Thermal Neutron Column," Greenhouse Report, Annex 2.2, Part II.

[4] R. E. Carter *et al.,* Greenhouse Report, Annex 2.4, Sec. 1, Chap. 2.

[5] R. E. Carter *et al.,* LA–1075, *op. cit.*

[6] J. T. Brennan *et al., op. cit.*

[7] R. E. Carter *et al.,* LA–1075, *op. cit.*

[8] J. T. Brennan *et al., op. cit.*

irradiated control groups. The per cent organ weight decrease is plotted against the log of the dose and the best curve of fit established by the method of least squares. The expression representing the relationship of dose to per cent organ weight decrease may be used to determine the dose in rem of an unknown radiation exposure by substituting the observed per cent organ weight decrease in the expression for the control studies and solving for dose.

3.3 DETERMINATION OF SPLENIC AND THYMIC WEIGHT LOSS

To determine the splenic and thymic weight loss as a result of radiation exposure it is necessary to compare the organ weights of irradiated animals with that of a similar group of unirradiated controls. Both control and irradiated animals are sacrificed with chloroform or ether 120 ± 3 hr after exposure. The spleen and thymus of each animal are removed and weighed individually to the nearest 0.2 mg. The spleen is weighed immediately with adequate precautions against loss of weight by drying. The thymus is placed in 10 per cent formalin for 24 hr to aid in the separation of adherent fat and connective tissue. After the period of fixation and the removal of the fat and connective tissue the organ is blotted dry and weighed. The organ weights of the unirradiated controls are determined at the same time and in the same manner. The mean percentage organ weight decrease for the irradiated groups is determined from the mean organ weight of the unirradiated controls.

Chapter 4

Experimental Method for Field Studies

4.1 DESCRIPTION OF APPARATUS

4.1.1 The Hemispherical Lead Shield

In addition to shielding from blast and flash the mice exposed in this experiment required complete protection against bomb gamma rays. It was desirable therefore to design a shield which would be opaque to gamma rays and relatively transparent to neutrons of all energies. On the basis of the known cross sections lead and bismuth were the only possible choices, and bismuth was eliminated by reason of cost. The shields were cast from commercial lead at the Los Alamos Scientific Laboratory. Spectrographic analysis of the lead showed that it contained no significant quantities of undesirable impurities. The analytical results are presented in Table 4.1.

The shields were cast in the form of hollow hemispherical shells with tapering cylindrical lead skirts (Fig. 4.1) to protect the animals from scattered radiation from the ground. The wall thickness of the hemisphere was 7 in. Animals were confined in the hemispherical cavity of 7-in. radius in the center of the shield. An access port, 4 in. in diameter and closed with a lead plug, was provided for introduction and withdrawal of the animals (Fig. 4.2). A neutron exposure station consisted of a lead hemisphere placed over the upper end of the cylindrical base of a gamma exposure unit. The bottom of the base was buried in the ground and was equipped with air intake and exhaust ducts and a ventilation mechanism (see Fig. 4.3). For further details of the exposure units see the container report.[1]

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[1] Greenhouse Report, Annex 2.3, Chap. 3.

TABLE 4.1 SPECTROGRAPHIC ANALYSIS[a] OF LEAD USED FOR FABRICATION OF GAMMA-RAY SHIELDS

ELEMENT[b]	σ_a[c]	ELEMENT[b]	σ_a[c]	ELEMENT[b]	σ_a[c]
Li —ND		Zn —ND		Ho —ND	
Be —ND		Y —ND		Er —ND	
B —ND		Mo—ND		Tm—ND	
Na—T	0.5	Rh—ND		Yb —ND	
Mg—FT	0.06	Ag —FT	60.0	Lu —ND	
Si —FT	0.1	Cd—ND		Hg—ND	
Ca —FT	0.5	In —ND		W —ND	
Sc —ND		Sn —ND		Os —ND	
Ti —ND		Pr —ND		Ir —ND	
V —ND		Nd—ND		Pb —VS	0.19
Cr —ND		Sm—ND		Bi —T-W	0.015
Mn—ND		Hf —ND			
Fe —T	2.5	Eu —ND			
Co —ND		Gd—ND			
Ni —ND		Tb —ND			
Cu —FT	3.6	Dy—ND			

[a] CMR Division, Group 1—LASL Plate No. 8194.
[b] Code: FT<0.001 per cent, T=0.001 to 0.01 per cent, W=0.01 to 0.1 per cent, VS>10 per cent, ND=not detected.
[c] Capture cross section for slow neutrons expressed in barns.

Certain of the lead shields were covered with cadmium sheet. This covering extended over the entire outer surface of the hemispherical and skirt portion of the shield. The cadmium thickness was $\frac{1}{32}$ in. and the sheets were secured to the lead with sheet-metal screws.

4.1.2 Placement of the Lead Hemisphere Stations

The choice of the locations of the neutron stations was highly uncertain because of the absence of any information about the neutron spectrum between 0.4 ev and 3 Mev and the general lack of reliable figures for the biologi-

cal effectiveness of neutrons of the various energies.

It was decided, therefore, to place the stations in accordance with the gold and sulfur neutron fluxes predicted from previous tests. All other uncertainties, including the contribution due to neutrons of intermediate energy, had to be allowed for by increasing the spread between the closest and the most distant stations. The location of the neutron stations for Dog Shot was based on an early predicted yield of 140 kt instead of the revised yield prediction of 90 kt. The placement of the stations on the basis of the larger yield prediction was responsible for the good results obtained on Dog Shot. The neutron exposure stations for Easy Shot were placed on the basis of an estimated yield of 50 kt. The significance of the good results obtained on Dog Shot and the influence of bomb assembly on neutron flux were not realized at the time the stations for Easy Shot were located; as a result all the stations except the most distant ones were overexposed. The number of stations for George Shot was increased on the basis of the data collected from the two previous shots and they were located on the basis of an estimated yield of 250 kt.

In general the flux and the effectiveness of bomb neutrons were underestimated and the stations for all three shots were placed too close to ground zero. However, on two of the three shots the data obtained were sufficient to provide reliable curves for neutron dose in rem vs distance. The locations of the neutron stations on all three shots are given in Table 5.1.

4.2 DESCRIPTION OF BIOLOGICAL PROCEDURES

4.2.1 Selection of Animals

Animals used in the three shots were selected in the following manner: From the total number of animals available in the colony for the field tests, those animals whose ages fell between 7 and 9 weeks at test time were selected. From this population, female animals whose body weights fell between 20.0 and 23.9 g were used. For each shot, the animals selected

were divided into experimental groups of 20 or 30 each in a random manner with respect to age and weight. The selection of animals for loading into exposure cages and units was made according to a table of random numbers.

Both general and special control groups were kept for each shot. The control animals were selected in a manner identical with that used for the animals destined to be exposed. The general controls never left the animal quarters on Japtan Island. The special control groups were placed in exposure units in the field on the rehearsal which preceded each shot. Their transportation to and from the shot island, and the duration and conditions of confinement paralleled the actual shot conditions insofar as possible.

4.2.2 Field Control Studies

As mentioned in Sec. 3.2, in order to determine the biological effects of an unknown radiation exposure, it is necessary to conduct control experiments to determine the relationship of organ weight loss and dose of the reference radiation. Obviously the control experiments should be performed under conditions as closely approximating the actual field conditions as possible. Control studies were conducted, therefore, on Japtan using mice selected from the animal population used in the field experiment. Details of the field control studies, the method of exposing animals, selection of animals, and the analysis of data are given in the control report.[2] Initial analysis of the control data for the thymic weight loss for LAf_1 mice indicated that the relation between dose and weight loss could be analyzed as an exponential function over the range of only 150 to 700 r. It was found, however, that a probit transformation of the per cent thymic weight loss permitted the derivation of an exponential function which satisfactorily expressed the relation between effect and dose over the range 75 to 900 r. The best expression for the control studies of thymic weight loss as a function of dose for LAf_1 female mice under field conditions was

$$w = 0.1239 + 2.1557 \log r \pm 0.186$$

where r is the dose of 230–KVP X radiation in

[2] Greenhouse Report, Annex 2.2, Part I.

roentgens, w is the empirical probit transformation of the per cent thymic weight loss and 0.186 denotes the estimated standard deviation from the regression (standard error of estimate). The above expression and the points collected in the field control study are shown graphically in Fig. 4.4.

Control studies using the spleen showed that there was very little added splenic weight decrease at doses greater than 500 r. The relatively short dosage range over which the splenic response in LAf_1 mice could be used and the great inherent error in the results with this strain made the spleen results of use only for substantiating the thymic results at the intermediate dose stations. In the control study the splenic weight loss with 900 r was taken as the maximum weight loss which could be produced in this strain of mice. Taking the weight loss seen at 900 r as 100 per cent, the per cent weight losses observed at the other doses were adjusted accordingly. The best eye-fitted curve was drawn through the resultant points. The curve for the splenic response of LAf_1 female animals is given in the control report.[3]

4.2.3 Placement and Recovery of Animals

Animals were transferred from animal colony cages to exposure cages 20 ± 2 hr before

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[3] Greenhouse Report, Annex 2.2, Part I.

each shot. The exposure cages were of two sizes, the larger measuring 2 by 2 by 10 in., the smaller 2 by 2 by 6 in. The cages were constructed of galvanized iron wire, ¼-in. mesh, on five sides and were closed on one end with ½-in.-thick wood plugs (see Fig. 4.3). For Dog and Easy Shots, 7 animals were placed in each of 2 large cages, 4 animals in 1 small cage, and 3 animals in each of 4 small cages in each exposure station. For George Shot, 5 animals were placed in each of 2 large cages, and 2 animals in each of 5 small cages. Watering tins were placed in each cage, providing 60 cc of water in the case of the large cages and 30 cc for the small cages. Each animal was supplied 10 g of food. Cages were transported to the shot islands in cylinder liners by truck and landing craft. As soon as possible after each shot (6 ± 3 hr), animals were removed from the exposure containers and returned to the animal colony in the manner described above. Animals were back in colony cages an average of 8 hr after each shot.

4.2.4 Determination of Splenic and Thymic Weight Loss

The weight of the spleen and thymus of control and exposed animals was determined 5 days after exposure according to the methods described in Sec. 3.3.

Chapter 5

Experimental Results

5.1 BIOLOGICAL MEASUREMENTS

The biological results obtained on Dog, Easy, and George Shots are presented in Table 5.1. These data show the station locations, the per cent thymic and splenic weight loss, and the neutron dose in rem derived from the expression for the field control study. The number of animals surviving to the 5th day after exposure is shown. Occasionally animals were lost or fatally injured before the 5th day,

TABLE 5.1 LOCATION OF NEUTRON STATIONS AND RESULTS OF SPLEEN-THYMUS STUDIES FOR DOG, EASY, AND GEORGE SHOTS

SHOT	STATION NO.	DISTANCE (yd)	PER CENT THYMUS WEIGHT LOSS	NEUTRON DOSE (rem)	PER CENT SPLEEN WEIGHT LOSS USING GREATEST LOSS AS 100 PER CENT	NEUTRON DOSE (rem)	NUMBER OF ANIMALS DEAD BEFORE D+5
Dog	73a	900	93.9	>900	100	>600	27
	73b	900	92.5	>900	96.8	>600	27
	73c	1,000	89.5	699	86.8	>600	0
	73d(a)	1,000	87.6	629	83.0	460	0
	73e	1,100	70.8	328	63.3	280	0
	73f	1,100	67.9	301	63.8	280	0
	73g	1,200	53.6	201	19.7	170	0
	73h	1,300	33.8	117	7.4	120	0
Easy	73a	675		>900			30
	73b	675		>900			30
	73c	700		>900			30
	73d(a)	700		>900			30
	73e	775		>900			30
	73f	775		>900			30
	73g	875	94.3	>900		>600	26
	73h	1,000	85.3	560		370	0
George	73a	1,000		>900	100	>600	30
	73b	1,050		>900	100	>600	30
	73c	1,100		>900	100	>600	30
	73d	1,150		>900	100	>600	30
	73e	1,200	89.8	>900	100	>600	21
	73f	1,250	89.4	691	99.6	>600	0
	73g	1,300	84.3	536	90.1	600	0
	73h	1,350	77.9	416	82.3	430	0
	73i	1,400	61.2	248	70.1	310	0
	73j	1,450	48.5	176	48.5	240	0
	73k	1,500	39.9	139	30.2	200	0

(a) Indicates cadmium-covered station.

which resulted in fewer animals in a particular group. No animals or individual organs were excluded from the study except where the organ weight decrease for any group fell outside the range covered by the control studies. In these instances the rem equivalent of 230-KVP X-ray irradiation could not be determined. These groups are shown in Table 5.1 with the notation that the equivalent dose to the spleen was greater than 600 rem and to the thymus was greater than 900 rem. The spleen results and those results not within the accepted range of the method have not been used in subsequent determinations and discussions.

The curves showing rem vs distance from ground zero for Dog and George Shots are plotted in Figs. 5.1 and 5.2. The difference in distance using ground zero instead of air zero for tower shots is negligible over the biological range of interest. The single point available from Easy Shot is shown on the Dog Shot curve but was not used in the calculation. The cadmium-covered station on Dog Shot is not shown. The best curves of fit for both Dog and George Shots were the following quadratics:

Dog, $\log \text{rem} = 9.59497 - 1.00393 \times 10^{-2}D + 3.27612 \times 10^{-6}D^2$, $\quad S^2 = 9.387 \times 10^{-4}$

George, $\log \text{rem} = 4.98220 - 6.61359 \times 10^{-4}D - 8.31286 \times 10^{-7}D^2$, $\quad S^2 = 1.641 \times 10^{-3}$

The standard error of estimate, S^2, is shown in each case.

5.2 PHYSICAL MEASUREMENTS

The physical results presented in this section were used primarily to determine the influence of the lead on bomb neutron dose. The values have been collected from a variety of sources and in some cases are still provisional.

Figure 5.3 shows the gamma dose (in roentgens) plotted against distance from ground zero for Dog, Easy, and George Shots. These curves were derived from the NBS data. The graphs were used to determine the ratios of neutron to gamma-ray dose for the various detonations.

Figures 5.4 and 5.5 show neutron flux$\times$(distance)^2 plotted against distance for Dog and George Shots. The neutron flux measurements are taken from data collected by Group J-12 of the Los Alamos Scientific Laboratory. The thymus data are included also by plotting rem$\times$(distance)^2 vs distance. An exponential plot of this type was used to facilitate comparison and discussion. The error is greater than for the quadratic forms given above but it introduces no serious hazards in interpretation. A summary of the mathematical treatment of all physical and biological results are presented in Table 5.2. Values listed under a are the intercepts of the theoretically determined regression lines. The b values are the slopes of the various regression lines. The $V(b)$ values are the respective variances of the slopes and are useful in determining the significance of variations in slopes.

TABLE 5.2 SUMMARY OF MATHEMATICAL TREATMENT OF BIOLOGICAL AND PHYSICAL DATA

Dog Shot Equations:
1. Thymus, $\log (\mathrm{rem} \times D^2) = 10.51165 - 0.0017184D$
2. Gold outside, $\log (nvt \times D^2) = 19.78513 - 0.0025059D$
3. Gold inside, $\log (nvt \times D^2) = 19.73007 - 0.0025467D$
4. Sulfur outside, $\log (nvt \times D^2) = 18.02268 - 0.0019788D$

George Shot Equations:
1. Thymus, $\log (\mathrm{rem} \times D^2) = 11.95211 - 0.0023142D$
2. Gold outside, $\log (nvt \times D^2) = 20.44974 - 0.0022544D$
3. Gold inside, $\log (nvt \times D^2) = 20.42986 - 0.0023841D$
4. Sulfur outside, $\log (nvt \times D^2) = 18.98741 - 0.0017882D$
5. Sulfur inside, $\log (nvt \times D^2) = 18.43848 - 0.0018988D$

COLLECTED PARAMETERS

SHOT	MEASUREMENT	INTERCEPT VALUE a	SLOPE VALUE b	VARIANCE IN b $V(b)$	STANDARD ERROR OF ESTIMATE (S^2)
Dog	Thymus	10.51165	-0.0017184	4.7087×10^{-8}	0.0244855
Dog	Gold outside	19.78513	-0.0025059	4.9258×10^{-9}	0.0013218
Dog	Gold inside	19.73007	-0.0025467	1.6642×10^{-9}	0.0001664
Dog	Sulfur outside	18.02268	-0.0019788	1.7356×10^{-8}	0.0097193
George	Thymus	11.95211	-0.0023142	3.0201×10^{-8}	0.0013213
George	Gold outside	20.44974	-0.0022544	3.9671×10^{-8}	0.0025408
George	Gold inside	20.42986	-0.0023841	3.2583×10^{-8}	0.0163847
George	Sulfur outside	18.98741	-0.0017882	2.0234×10^{-8}	0.0046205
George	Sulfur inside	18.43848	-0.0018988	2.7030×10^{-9}	0.0014113

$V(b) = \sigma_b^2$; σ_b is the standard deviation of b, the slope of the regression line.

Chapter 6

Effect of Lead Shield on Bomb Radiation

In order to protect the mice from bomb gamma rays it was necessary that they be exposed behind 7 in. of lead as described above. Actually the purpose of the experiment was to determine the neutron dose to an unshielded animal. It is necessary therefore to consider in detail the influence of the lead shield on (a) the gamma dose to mice, and (b) the neutron dose received by the mice.

6.1 GAMMA FLUX INSIDE THE LEAD HEMISPHERE

It is desirable that the gamma flux inside the lead hemisphere not contribute significantly to the biological effect observed. Gamma rays which reach the central cavity in the lead result directly from the bomb or from (n,γ) reactions in the shield.

6.1.1 Absorption of Bomb Gamma Flux

Gamma rays impinging on the surface of the lead hemisphere are nearly all absorbed in the lead. In good geometry the most penetrating gamma rays (~ 3 Mev) with a total absorption coefficient $\mu_t = 0.46$ cm^{-1} are attenuated by 7 in. of lead as follows:

$$\frac{I}{I_0} = e^{-\mu_t z} = 0.00028.$$

However, the hemisphere presents a condition of bad geometry and multiple scattering must be considered. The results of Hirschfelder and Adams [1] indicate a transmission of

$$\frac{I}{I_0} = 0.001$$

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[1] J. D. Hirschfelder and E. N. Adams, *Physical Review*, LXXIII (1948), 863–868.

in a bad geometry situation. The highest incident gamma dose at any hemisphere from which usable biological data was obtained may be estimated as not greater than 30,000 r. The bomb gamma dose inside this hemisphere was therefore less than 30 r, which represents less than 5 per cent of the total neutron dose.

6.1.2 Absorption of Secondary Gamma Rays Arising in the Lead

Secondary gamma rays are created in the lead by the inelastic scattering of high-energy neutrons. These gamma rays are absorbed in the lead and few reach the mice. By making the following conservative assumptions an upper limit of the dose delivered to the mice can be estimated:

(a) The secondary gamma rays created have maximum transmission in lead, i.e., energy ≈ 3 Mev and the absorption coefficient $\mu_t = 0.46$ cm^{-1}.

(b) The highest total neutron flux reaching any hemisphere was 2×10^{11} neutrons/cm^2. This value is established from the estimate that the total number of neutrons of all energies reaching a given point is about twice the measured gold neutron flux at that point.[2] In the following calculation a value of 10^{12} neutrons/cm^2 was used.

(c) Neutrons inelastically scattered in lead produce 3-Mev gamma photons.

Consider a lead hemisphere with a hemispherical central cavity and internal and external radii of r_1 and r_2, respectively. The neutron flux incident on the outer surface is N_0 neutrons/cm^2 (assumed normal to the sur-

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[2] *The Effects of Atomic Weapons* (Los Alamos Scientific Laboratory and U. S. Government Printing Office, Washington, D. C., 1950) p 244.

face). The neutron flux N_1 within the lead, at distance r from the center of the cavity, is

$$N_1 = N_0 e^{-\mu_n(r_2-r)}$$

and at a distance $r+dr$ from the center of the cavity is

$$N_2 = N_0 e^{-\mu_n[r_2-(r+dr)]}$$

where μ_n is the linear absorption coefficient for neutrons. Thus the photon flux, I (photons/cm^2), produced in this interval is $N_2 - N_1$ or

$$I = N_0 \left\{ e^{-\mu_n[r_2-(r+dr)]} - e^{-\mu_n(r_2-r)} \right\}$$

or

$$I = N_0 \left[e^{-\mu_n(r_2-r)}(e^{\mu_n dr} - 1) \right].$$

Since $\mu_n dr$ (for lead) is very small,

$$e^{\mu_n dr} - 1 \approx \mu_n dr$$

and

$$I \approx N_0 \mu_n e^{-\mu_n(r_2-r)} dr.$$

Neglecting absorption of these photons in remaining lead, the differential gamma flux at the center of the cavity, I_c, due to a hemispherical shell of radius r is

$$I_c = \frac{KN_0\mu_n e^{-\mu_n(r_2-r)}(2\pi r^2)dr}{r^2}$$

where K is a constant determined by measuring the photon flux at 1 cm from a point source of the activated lead.

If gamma absorption is considered, the coefficient $e^{-\mu_\gamma(r-r_1)}$ is introduced so that

$$I_c = 2\pi KN_0\mu_n e^{-\mu_n(r_2-r)} e^{-\mu_\gamma(r-r_1)} dr$$

and the total photon flux at the center of the cavity due to the whole hemisphere is

$$I_T = 2\pi KN_0\mu_n \int_{r_1}^{r_2} e^{[-\mu_n(r_2-r)-\mu_\gamma(r-r_1)]} dr.$$

Integration of the above expression gives

$$I_T = \frac{2\pi KN_0\mu_n}{\mu_n - \mu_\gamma} \left[e^{-\mu_\gamma(r_2-r_1)} - e^{-\mu_n(r_2-r_1)} \right].$$

Since gamma absorption in lead is very large compared to neutron interaction, the term $e^{-\mu_\gamma(r_2-r_1)}$ is small and may be neglected, so:

$$I_T = \frac{2\pi KN_0\mu_n}{\mu_\gamma - \mu_n} \left[e^{-\mu_n(r_2-r_1)} \right].$$

I_T may be maximized by differentiating with respect to μ_n and equating to zero:

$$\frac{dI_T}{d\mu_n} = 2\pi KN_0 \left[\frac{1}{\mu_\gamma - \mu_n} e^{-\mu_n(r_2-r_1)} \right.$$
$$\left. + \frac{\mu_n}{(\mu_\gamma - \mu_n)^2} e^{-\mu_n(r_2-r_1)} - \frac{(r_2-r_1)\mu_n}{\mu_\gamma - \mu_n} e^{-\mu_n(r_2-r_1)} \right].$$

In this case

$$\mu_n = \frac{\mu_\gamma(r_2-r_1) \pm \sqrt{[\mu_\gamma(r_2-r_1)]^2 - 4\mu_\gamma(r_2-r_1)}}{2(r_2-r_1)}.$$

Since $\mu_\gamma = 0.46$ cm^{-1} and $r_2 - r_1 = 17.78$ cm, then $\mu_n = 0.0656$ or 0.3944 cm^{-1}. I_T is evaluated by substitution. $N_0 = 10^{12}$ neutrons/cm^2 and $2\pi K$ is equal to one-half the absolute source strength (from the definition of K). I_T is maximized therefore when $\mu_n = 0.0656$ cm^{-1} and equals 2.6×10^{10} photons.

Since 10^9 photons are equivalent to 1 r (footnote 3) the maximum dose is ~ 26 r. In view of the fact that the assumptions tend to maximize the dose, it is probable that the actual dose is much smaller and may be neglected.

6.2 MODIFICATION OF THE BOMB NEUTRON FLUX BY LEAD HEMISPHERES

It was realized at the outset that the hemisphere would inevitably alter the total number, spectrum, and direction of the bomb neutrons reaching the mice and that there would therefore be a difference between the biological effect of the neutron flux observed inside and outside the lead shield.

[3] W. V. Mayneord, *British Journal of Radiology*, Supplement No. 2 (1950), 136.

The neutron data presented in Figs. 5.4 and 5.5 and certain theoretical considerations will be discussed in the following sections in an effort to determine the variation in the biological effect caused by the interposed lead shield.

6.2.1 Modification of the Gold Neutron Flux

The physical data given in Figs. 5.4 and 5.5 and in Table 5.1 show the following:

(a) Apparent transmission of 80 per cent of gold neutrons on Dog Shot.

(b) Apparent transmission of 60 per cent of gold neutrons on George Shot.

(c) No significant differences in slope of the curve for gold neutrons outside and gold neutrons inside.

(d) No significant differences in slope for gold neutrons from shot to shot.

The observed transmission of gold neutrons by the shield may be compared with the theoretical values derived below by considering the fact that, in lead, gold neutrons can undergo two interreactions, namely elastic scattering and capture.

6.2.1.1 Elastic Scattering of Gold Neutrons in Lead

Since lead is an element of high atomic weight ($A=207$), the energy lost per collision by the neutron in the scattering process is

$$E = E_0 \, \frac{2A}{(A+1)^2} = \frac{2}{A} E_0 = 0.01 E_0$$

where E_0 is the initial energy of the neutron.[4]

Since elastic scattering is the primary process the mean free path, λ, of the neutrons in lead may be evaluated as

$$\lambda = \frac{1}{\mu_n} = \frac{A}{\sigma_t N_e} = 2.41 \text{ cm}$$

where

$\sigma \approx \sigma_t = 13$ barns

$N = 6.02 \times 10^{23}$, gram atom weight

$A = 207.21$

$\rho = 11$ g/cc, density of lead

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[4] W. E. Siri, *Isotopic Tracers and Nuclear Radiations* (New York: McGraw-Hill, 1949) p 124.

The lead hemisphere wall was 17.78 cm thick. Diffusing through this thickness of lead, where the loss of energy per collision is small and all scattering angles are about equally probable, the gold neutrons will on the average travel a mean path length (MPL) of:

$$\text{MPL} = \frac{(17.78)^2}{2.41} = 131 \text{ cm}$$

and will have $N = \dfrac{131}{2.41} = 54.4$ collisions.

Therefore, gold neutrons will retain a fraction of their energy equal to:

$$(E_0 - E)^N = (0.99 E_0)^{54.4} = 0.58 E_0$$

in the diffusion process.

Since gold neutrons are random in direction before they reach the lead, a change in direction due to elastic scattering does not change the number of gold neutrons reaching the mice. Therefore, the net effect of elastic scattering of gold neutrons by the lead is no change in flux but a loss of about one-half their initial energy.

6.2.1.2 The Capture of Gold Neutrons in Lead

The capture cross section, σ_c, for gold neutrons in lead is 0.19 barn at 0.025 ev and varies as $1/v$ where v is neutron velocity. For this reason elastic scattering is dominant over capture as far as number of reactions is concerned.

Taking 0.19 barn as the effective average capture cross section for gold neutrons, the fraction transmitted through the lead to the cavity is:

$$\frac{I}{I_0} = e^{-\sigma_c N x} = \exp(-0.19 \times 10^{-24} \times 3.2 \times 10^{22} \times 131) = 0.45$$

where

$N =$ lead atoms/cc of lead

$x =$ mean path length in lead, cm

This calculated transmission of 0.45 may be compared with the observed transmission of 0.80 for Dog Shot and 0.6 for George Shot. The difference is due to the moderation of epi-

cadmium neutrons with energies greater than 0.4 ev by the lead. This is demonstrated in the following section.

6.2.1.3 Apparent Increase in Gold Neutron Transmission due to Moderation of Epi-cadmium Neutrons

It has been shown above that gold neutrons will, on the average, lose about 42 per cent of their energy in diffusing through 7 in. of lead. Epi-cadmium neutrons with energies greater than 0.4 ev will be similarly moderated. Neutrons in the energy range 0.4 to 0.4/0.58 ev (0.4 to 0.7 ev) will be moderated by the lead to energies which will not be detected by cadmium-covered gold foils. The data in Table 6.1 illustrate this result.

Station 73d was a lead hemisphere station identical with any other except that the outside was covered with a sheet of cadmium $\frac{1}{32}$ in. thick. Thus all gold neutrons impinging on the hemisphere were captured at the surface and did not enter the lead. The difference between the bare gold foil and the cadmium-covered foil inside this station can only be accounted for by the moderation of neutrons from energies above the 0.4-ev cadmium cutoff to energies in the cadmium capture region. The results indicate that 44 per cent of the gold neutron activity is accounted for by moderation of epi-cadmium neutrons. The calculated transmission of 45 per cent plus the 44 per cent activity due to moderated epi-cadmium neutrons is in good agreement with the 80 per cent transmission observed on Dog Shot.

No data on cadmium-covered stations were available on George Shot. The lower apparent transmission of 60 per cent can be accounted for by assuming a lower proportion of epi-cadmium (0.4 to 0.7 ev) neutrons to gold neutrons for this particular assembly. The result is reasonable with the spectral shift to higher energies observed by other experimenters on George Shot.

In summary, use of the lead hemispheres caused a net decrease in total flux of gold neutrons of 20 to 40 per cent by capture and an average energy loss per neutron of about one-half.

6.2.2 Modification of Sulfur Neutrons by Lead Hemispheres

The data indicate an apparent transmission of 20 per cent of the sulfur neutrons on George Shot, and no significant difference in slopes over the biological range from outside to inside the lead.

The results must be accounted for by the fact that sulfur neutrons (>3 Mev) undergo only two types of reaction with lead. The reactions of importance are elastic and inelastic scattering. Capture is negligible.

6.2.2.1 Elastic Scattering of Sulfur Neutrons

Under the conditions of the experiment the hemispheres are scatterers of semi-infinite dimensions close to the sulfur detectors and distant from the source. The geometry is essentially identical to that employed by Phillips.[5] Under these conditions loss of neutrons by elastic scattering is negligible in that for every neutron scattered away from the detector another is scattered into it. Since the total loss of energy of a sulfur neutron is small (<10 per cent) in the few elastic scattering collisions

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[5] D. D. Phillips, Los Alamos Scientific Laboratory Report LA–740 (1949).

TABLE 6.1   GOLD NEUTRON FLUX MEASUREMENTS AT THE PAIRED STATIONS AT 1,000 YD ON DOG SHOT

STA-TION NO.	LOCATION OF FOIL	BARE AU FOIL COUNT	CD-COVERED AU FOIL COUNT	DIFFER-ENCE	AU NEUTRON FLUX (neutrons/cm²)	PER CENT OF INCIDENT AU NEUTRON FLUX
	Outside hemisphere	518,300	277,900	240,400	1.94×10^{11}	
73c	Inside Pb station	349,100	153,000	196,000	1.57×10^{11}	81
73d	Inside Cd-covered station	271,300	164,500	106,800	0.86×10^{11}	44

occurring in 7 in. of lead a negligible number of neutrons are degraded in energy to below the sulfur neutron threshold (3 Mev) by this process. The net flux change is therefore negligible.

6.2.2.2 Inelastic Scattering of Sulfur Neutrons

The total cross section for neutrons (3- to 15-Mev energy range) in lead, σ_t, is constant at about 5.2 barns. Since σ_c (capture cross section) in lead is negligible at these energies

$$\sigma_t = \sigma_e + \sigma_{in}$$

σ_e = elastic scattering cross section

σ_{in} = inelastic scattering cross section.

The measured values of σ_{in} indicate that the inelastic scattering cross section is constant and about equal to σ_e for widely different energies. [6-8] By inference from theoretical considerations σ_{in} may be considered to be constant over the energy range 3 to 15 Mev and a value of $\sigma_{in} = 2.3$ barns may be used.

Investigations of the inelastic scattering process in lead indicate that no matter what the initial energy of the neutron (3 to 15 Mev) the energy of the degraded neutron is in the 1- to 3-Mev range.[9-11] Thus, any sulfur neutron inelastically scattered will be degraded below the sulfur threshold and will not be detected by sulfur.

Using $\sigma_{in} = 2.3$ barns for sulfur neutrons and considering the fact that the mean path length for high-energy neutrons in lead is equal to the thickness, x, the transmisison of inelastically scattered sulfur neutrons is

$$\frac{I}{I_0} = e^{-\sigma_{in} Nx} = \exp(-2.3 \times 10^{-24} \times 3.2 \times 10^{22} \times 2.54 \times 7) = 0.27$$

The result agrees very well with the 20 per cent transmission found on George Shot. It is evident that inelastic scattering accounts for the apparent decrease in sulfur neutrons

[6] *Ibid.*

[7] P. Olum, AEC Declassified Document MDDC–266, p 41.

[8] C. E. Mandeville and C. P. Swann, Nuclear Energy for Propulsion of Aircraft Report NEPA–1656 (1951).

[9] D. D. Phillips, *op. cit.*

[10] P. Olum, *op. cit.*

[11] C. E. Mandeville and C. P. Swann, *op. cit.*

inside the lead. If (as is probable), σ_{in} and σ_e are constant over the range 3 to 15 Mev an apparent transmission of 20 per cent may be assumed for sulfur neutrons on both Dog and Easy Shots, for which no data are available.

In summary, the net effect of the lead is a degradation of 80 per cent of the sulfur neutrons into the 1- to 3-Mev energy range with no loss in total flux above 1 Mev.

6.2.3 Modification of Intermediate Energy Neutrons by Lead Hemispheres

Although no physical data are available on neutrons between the energies 0.4 ev and 3 Mev an evaluation of the lead effect can be made from a knowledge of the interactions which occur.

Intermediate energy neutrons undergo five different kinds of reactions in lead. They are:

(a) Potential scattering—an (n,n) reaction in which the energy of the neutron is unchanged, but its path direction is changed. Since the lead shield is a semi-infinite scatterer the reaction results in no net loss in total neutron flux or energy.

(b) Resonance scattering—in this reaction the result is the same as in (a).

(c) Capture—since the capture cross section in lead is small even for gold neutrons and varies as $1/v$ the net loss of intermediate energy neutrons is negligible.

(d) Elastic scattering—the total flux remains the same but loss of energy occurs. The energy loss above 0.1 Mev is less than 10 per cent and increases at lower energies to a maximum of 42 per cent in the 0.4- to 0.7-ev range as shown in Sec. 6.2.1.1.

(e) Inelastic scattering—the inelastic scattering cross section becomes zero at about 1 Mev. Any neutrons in the 1- to 3-Mev range which are inelastically scattered will remain in this energy interval.

In summary, although no experimental data are available, it may be inferred from indirect evidence that the net effect of the above processes in lead is to decrease the over-all energy spectrum for intermediate neutrons to a small extent and to negligibly decrease the total flux.

6.3 SUMMARY

For the evaluation of the biological effects of bomb neutrons the physical processes involved are:

(a) An apparent transmission of gold neutrons on Dog and Easy Shots of 80 per cent and of 60 per cent on George Shot. About one-half of these neutrons are those which were in the energy range 0 to 0.4 ev outside the lead. The remainder were in the range 0.4 to 0.7 ev outside the lead.

(b) An apparent transmission of sulfur neutrons of 20 per cent on all shots. The 80 per cent not apparent have been degraded to the 1- to 3-Mev range regardless of their initial energy and are thus below the sulfur threshold.

(c) A negligible change in total flux and a negligible decrease in total energy for intermediate energy neutrons.

Chapter 7

Evaluation and Discussion of Results

7.1 BIOLOGICAL EFFECTS OF BOMB NEUTRONS INSIDE LEAD HEMISPHERES

The biological results presented in Chap. 5 show that the spleen-thymus method effectively integrates the biological effect of all bomb neutrons over the limits of the method and therefore gives a measure of the radiation effect produced by neutrons through a 7-in. lead shield. An adequate relationship between neutron effect and a well-studied laboratory radiation source effect has been developed. Neutrons for which no physical data regarding either spectrum or flux are available presumably contribute to the total biological effect. Since the gamma shield has distorted the neutron energy and flux spectrum as shown in Chap. 6, a discussion of the biological effects in the absence of the shield will be developed in the following section.

7.2 BIOLOGICAL EFFECTS OF BOMB NEUTRONS OUTSIDE LEAD HEMISPHERES

7.2.1 Biological Effectiveness and Neutron Energy

In order to evaluate the biological importance of flux and energy modifications noted in Chap. 6, it is necessary to know the variation of biological effectiveness with neutron energy. Very few experimental results are available on this subject. Most of the results are theoretical, based on known tissue-neutron reactions. In the discussion the following values and theoretical conclusions will be used:

(a) For the 0- to 0.4-ev neutron energy range, 5.9×10^{-11} rem=1 neutron/cm².[1]

(b) For the 1- to 3-Mev neutron energy range, 1.6×10^{-8} rem=1 neutron/cm². This assumes 1 rep=4 rem for fast neutrons, which is conservative as most experiments indicate that 1 rep=2 to 3 rem.[2]

(c) For the 3- to 15-Mev neutron energy range, 2.0×10^{-8} rem=1 neutron/cm². Again, 1 rep=4 rem is assumed.

(d) Below 1 Mev to energies where capture processes become important (<25 ev) elastic scattering of tissue hydrogen is the primary cause of biological effect. Since, in this range, the scattering cross section is essentially constant, biological effect is directly proportional to energy and decreases with energy.

(e) The lowest excited levels in air are 4 Mev for nitrogen and 16 Mev for oxygen. This prohibits a "pile up" in the neutron spectrum at low intermediate levels, which further minimizes the biological effect in this spectral region.

7.2.2 Dog Shot

Using 5.9×10^{-11} rem/neutron/cm² for gold neutrons and the observed fluxes *outside* the lead (from Fig. 5.4) it can be calculated that over the biological range only 1 to 1.5 per cent of the total biological effect can be due to gold neutrons. The 20 per cent decrease in transmission further decreases their contribution to the total biological effect. In general the biological effect due to gold neutrons is insignificant and therefore the effect of the lead shield on the dose due to gold neutrons

[1] R. E. Zirkle, *Radiology,* XLIX (1947), 271–273.
[2] R. E. Zirkle and C. W. Hagen, Jr., Metallurgical Laboratory Report CH–3903, Part I (1950).

may be neglected. Table 6.1 shows that the total rem in the 1,000-yd cadmium-covered station was 10 per cent less than the total rem in the paired Station 73c. This difference is within the error of the method and is not significant.

The degrading of 80 per cent of the sulfur neutrons by the lead to the 1- to 3-Mev range decreases the biological effect of these neutrons from 2×10^{-8} rem/neutron/cm² to

$$0.8 \times 1.6 \times 10^{-8} + 0.2 \times 2 \times 10^{-8} = 1.64 \times 10^{-8} \text{ rem/neutron/cm}^2.$$

Using 1.64×10^{-8} rem/neutron/cm² for the sulfur neutrons and the observed fluxes *outside* the lead, it can be calculated that over the biological range 25 per cent of the total rem determined by the thymus inside the lead is due to sulfur neutrons.

The remaining 75 per cent of the total biological effect inside the lead must be due to intermediate neutrons unaffected by the lead.

The lead shield then decreases the total effect by only the fraction of effect contributed by degraded sulfur neutrons. The effect is decreased by

$$1 - \frac{0.25 \times 1.64 \times 10^{-8}}{2 \times 10^{-8} - 0.75} = 1 - 0.96 = 4 \text{ per cent.}$$

7.2.3 George Shot

The gold neutron fluxes on George Shot indicate that only 1.5 per cent of the total rem over the entire biological range is due to neutrons in the 0- to 0.4-ev range. As before, such a result is negligible and the shield makes no difference.

Over the biological range the measured sulfur neutron fluxes indicate that 75 to 95 per cent of the total rem inside the lead is due to neutrons with energies greater than 3 Mev outside the lead.

The remainder of the biological effect must again be due to unaffected intermediate energy neutrons.

In this case the lead evidently decreases the total biological effect by 10 to 16 per cent.

7.2.4 Easy Shot

On Easy Shot a biological result was obtained at the 1,000 yd station only. At this station the total dose inside the lead was 560 rem, the gold neutron flux outside the lead was 1.19×10^{11} neutrons/cm² and the sulfur neutron flux outside the lead was 1.53×10^{10} neutrons cm². The doses due to various neutron components inside the lead are as follows:

Gold neutrons: $1.19 \times 10^{11} \times 5.9 \times 10^{-11} \times 0.8 = 5.6$ rem $= 1$ per cent of the total neutron dose.

Sulfur neutrons: $1.53 \times 10^{10} \times 1.68 \times 10^{-8} = 257$ rem $= 46$ per cent of the total neutron dose.

Intermediate neutrons: $560 - 263 \approx 300$ rem $= 53$ per cent of the total neutron dose.

For Easy Shot the per cent of the total neutron dose lost by absorption in the lead shield was

$$\frac{1}{0.01 \times 1.2 + 0.46 \times 1.16 + 0.53}$$
$$= 7 \text{ per cent, or} \sim 40 \text{ rem.}$$

The total dose outside the hemisphere is then 600 rem, to which gold neutrons contribute 1 per cent, intermediate energy neutrons 50 per cent, and sulfur neutrons 49 per cent of the total effect.

7.3 INFLUENCE OF BOMB ASSEMBLY ON NEUTRON DOSE

At the single common distance, 1,000 yd, the ratio of the neutron dose on Easy to that on Dog Shot outside the lead is 600/728 rem $= 0.82$. The ratio of respective yields as determined by other experiments is 0.6. Comparing values at 1,300 yd results in a ratio of neutron dose on Dog to that on George Shot outside the lead of 122/536 rem ≈ 0.2. The ratio of yields for these two shots is ~ 0.4. In neither case are the dose ratios equal to the yield ratios. It is apparent that differences in the three assemblies do not permit scaling neutron dose with kilotonnage at any particular distance.

7.4 COMPARISON OF NEUTRON AND GAMMA-RAY DOSES FROM AN ATOMIC EXPLOSION

By an extrapolation of the gamma-ray vs distance curves plotted in Fig. 5.3 the neutron dose to gamma dose ratio for any particular shot can be determined. Since the slopes of the neutron dose vs distance curves and of the gamma dose vs distance curves are significantly different the ratios must be determined for the whole neutron biological range or for points with equivalent rem of neutrons for different bombs. Only a single point at 1,000 yd (560 rem) was available on Easy Shot. These comparisons are shown in Table 7.1. The data demonstrate the extent to which the gamma-ray to neutron dose ratios for Dog, Easy, and George Shots varied with weapon assembly. They also support the con-

TABLE 7.1 THE NEUTRON TO GAMMA-RAY DOSE RATIOS FOR DOG, EASY, AND GEORGE SHOTS AT POINTS OF EQUAL DISTANCE AND EQUAL NEUTRON DOSE (in rem)

REFERENCE POINT	NEUTRON TO GAMMA-RAY DOSE (per cent)		
	Dog	Easy	George
560 rem	3.6	11.4	1.8
1,000 yd	4.0	11.4	...
1,250 yd	3.0	....	1.5
1,500 yd	...	....	1.4

clusions drawn under Sec. 7.3 regarding the effect of bomb assembly on total neutron dose.

7.5 THE LD$_{50}$ DISTANCE FOR NEUTRONS

If 400 rem is taken as the LD$_{50}$ dose of neutrons for man, then the LD$_{50}$ distances for Dog, Easy, and George Shots were 1,075, 1,060 (extrapolated), and 1,360 yd, respectively.

Chapter 8

Summary and Conclusions

In summary it can be stated that the experiment was successful in its primary objective, which was the measurement of total bomb neutron biological effect vs distance in terms of a simple biological indicator of radiation effect.

Certain definite conclusions may be drawn from the results. The Dog and Easy bombs were typical of fission weapons. The George detonation was an experimental assembly resembling no present or contemplated weapon and therefore the results should be considered atypical.

(a) The fraction of the neutron dose due to gold neutrons is negligible.

(b) The biological effects of intermediate neutrons constituted from 50 to 75 per cent of the total neutron dose on Dog and Easy Shots. They constituted much less of the total neutron effect on George Shot.

(c) The biological effects of sulfur neutrons constituted 25 to 47 per cent of the total neutron dose on Dog and Easy Shots and 75 to 95 per cent of the neutron effect over the range of biological interest on George Shot.

(d) Over 90 per cent of the bomb neutron dose from any bomb is due to neutrons with energies greater than 1 Mev.

(e) Neutron dose does not scale directly as kilotonnage, but depends on the bomb assembly. Both Dog and Easy were fission bombs, differing only in yield and neutrons. From a knowledge of assemblies, it is reasonable to predict that the neutron dose per kiloton will be a minimum for the Dog type bomb, intermediate for an Easy type bomb and maximum for a Hiroshima type bomb. The George assembly cannot be used for prediction purposes.

(f) The ratio of neutron dose to gamma dose is not constant per kiloton. This result is also due to assembly characteristics. Similar predictions to those above can be made.

(g) Lead shields decrease the total neutron dose from 4 to 16 per cent depending principally on the proportion of intermediate neutrons to sulfur neutrons at any point in the biological range and the biological effectiveness of each.

(h) Evasive action by personnel is not effective against neutrons because the majority of the dose is delivered by fast neutrons.

(i) Shielding studies on neutrons can only be properly interpreted using biological systems. Only biological methods integrate the total neutron effects; physical methods do not cover the important intermediate energy neutron range. The spleen-thymus system used in this experiment was suitable for such investigations.

THRESHOLD DETECTOR
(Au OR S)

←—BOMB

7"

LEAD
HEMISPHERES

LEAD SKIRT

MICE

12"

2"

MEAN GROUND
LINE

VENTILATION
MECHANISM

ALUMINUM BASE
TO GAMMA EX-
POSURE UNIT
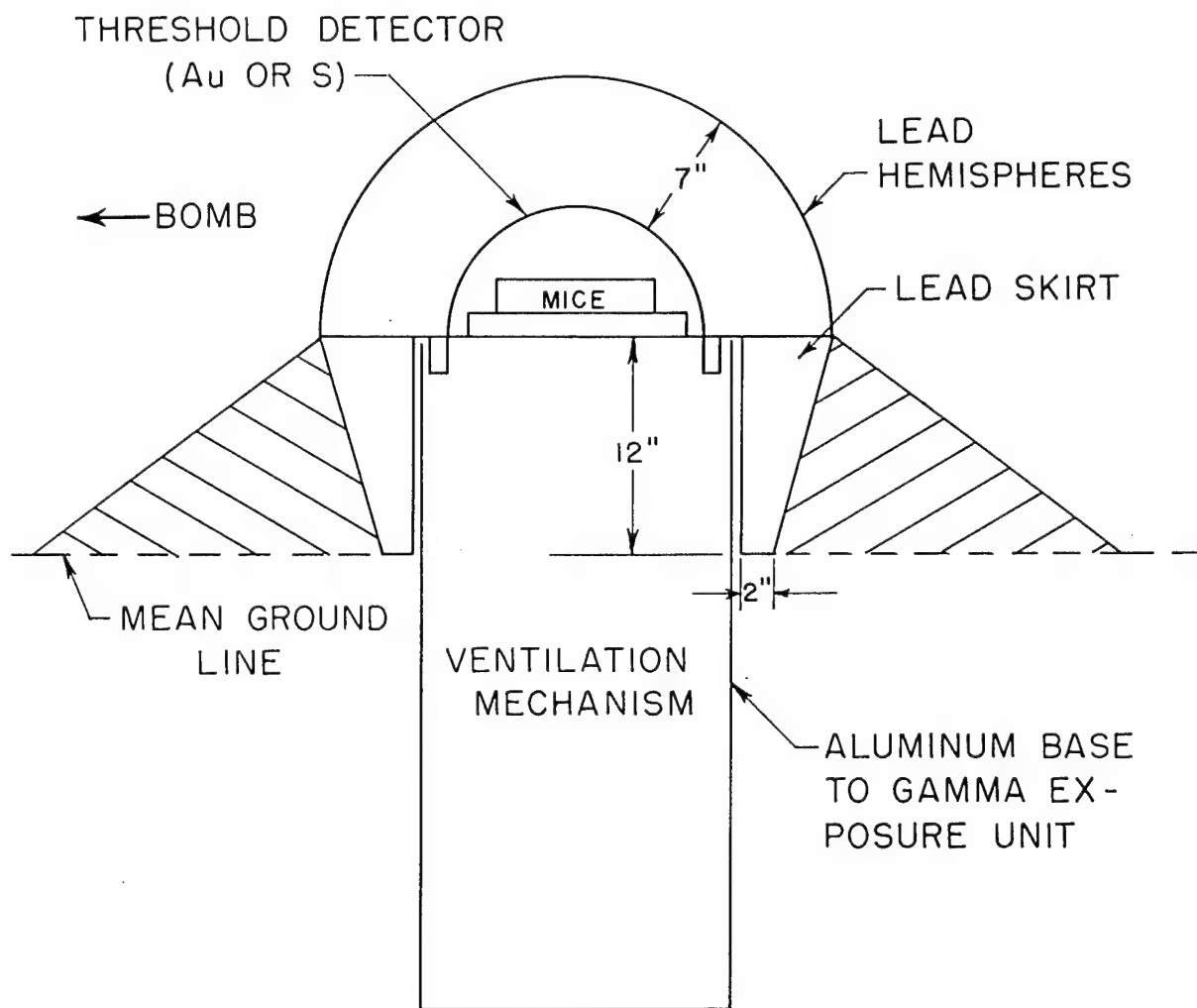
FIG. 4.1   Cross-sectional Sketch of Hemispherical Lead Shield

Fig. 4.2 Neutron Exposure Station Showing Lead Hemisphere Access Plug and Air Intake and Exhaust Ports
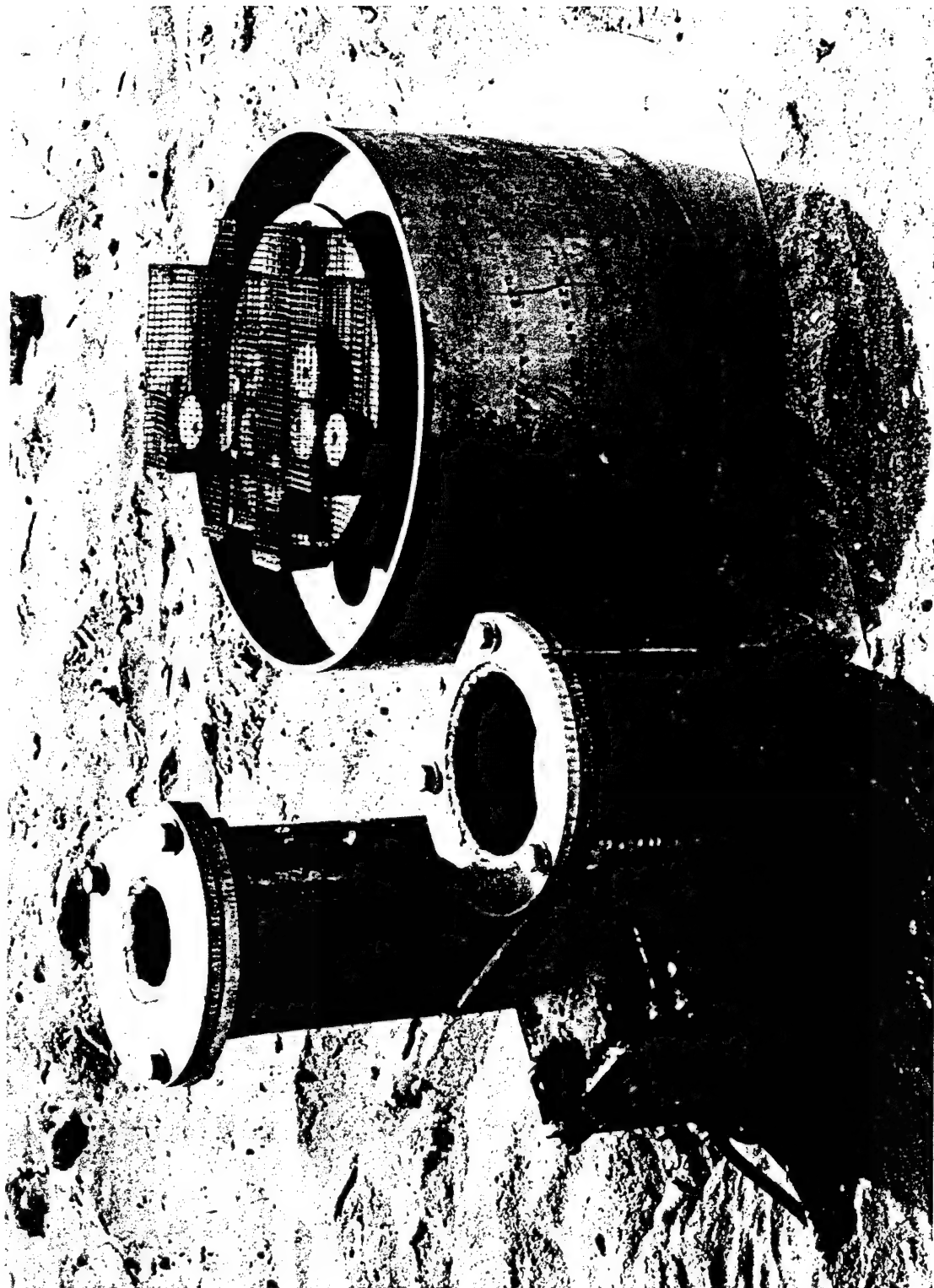
Fig. 4.3 Neutron Exposure Station with Lead Shield Removed Showing Aluminum Base, Ventilation Mechanism, and Animal Exposure Cages
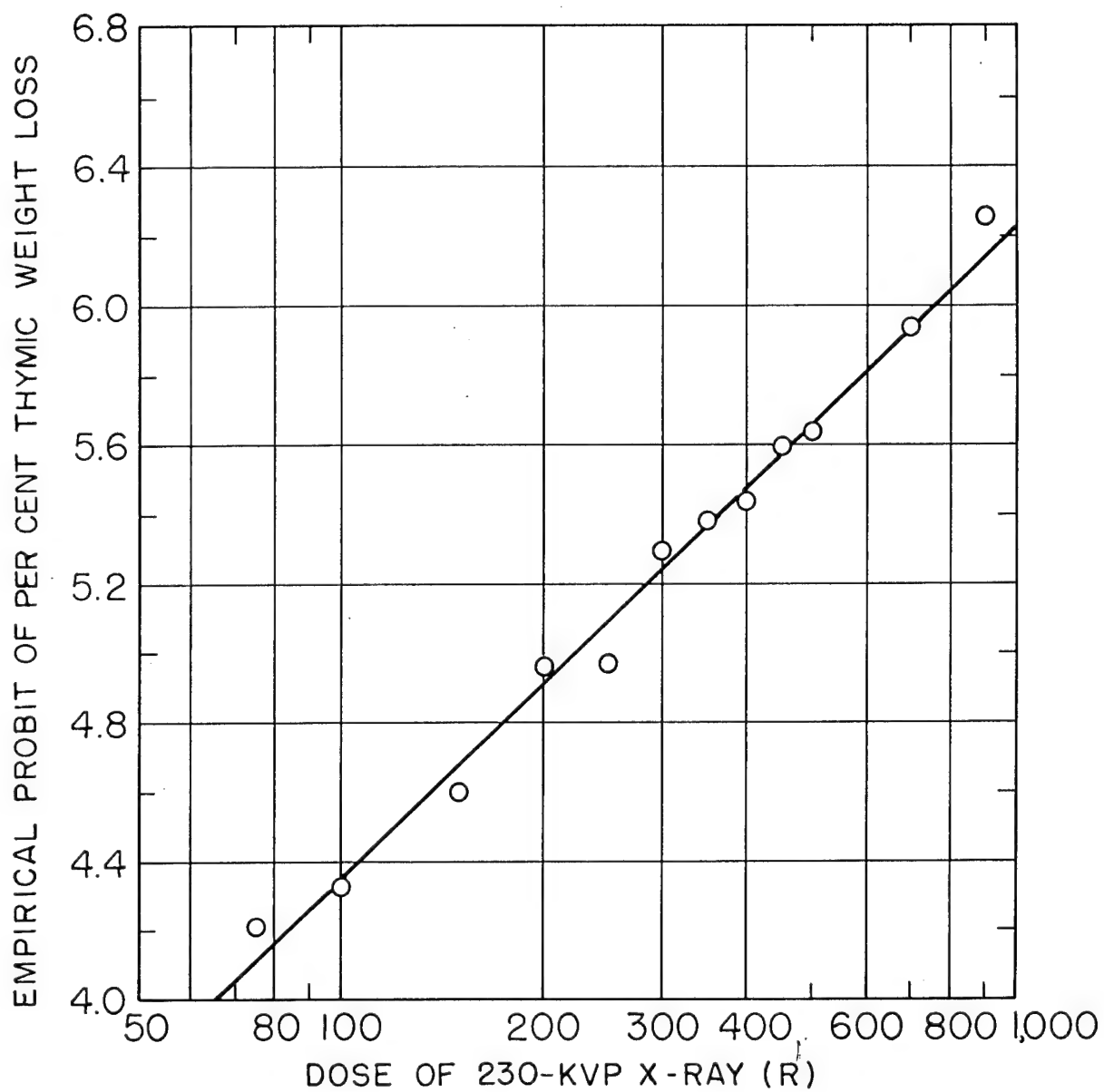
Fig. 4.4 Empirical Probit of Per Cent Thymic Weight Loss as a Function of Dose of 230-KVP X Rays in Field Control Study
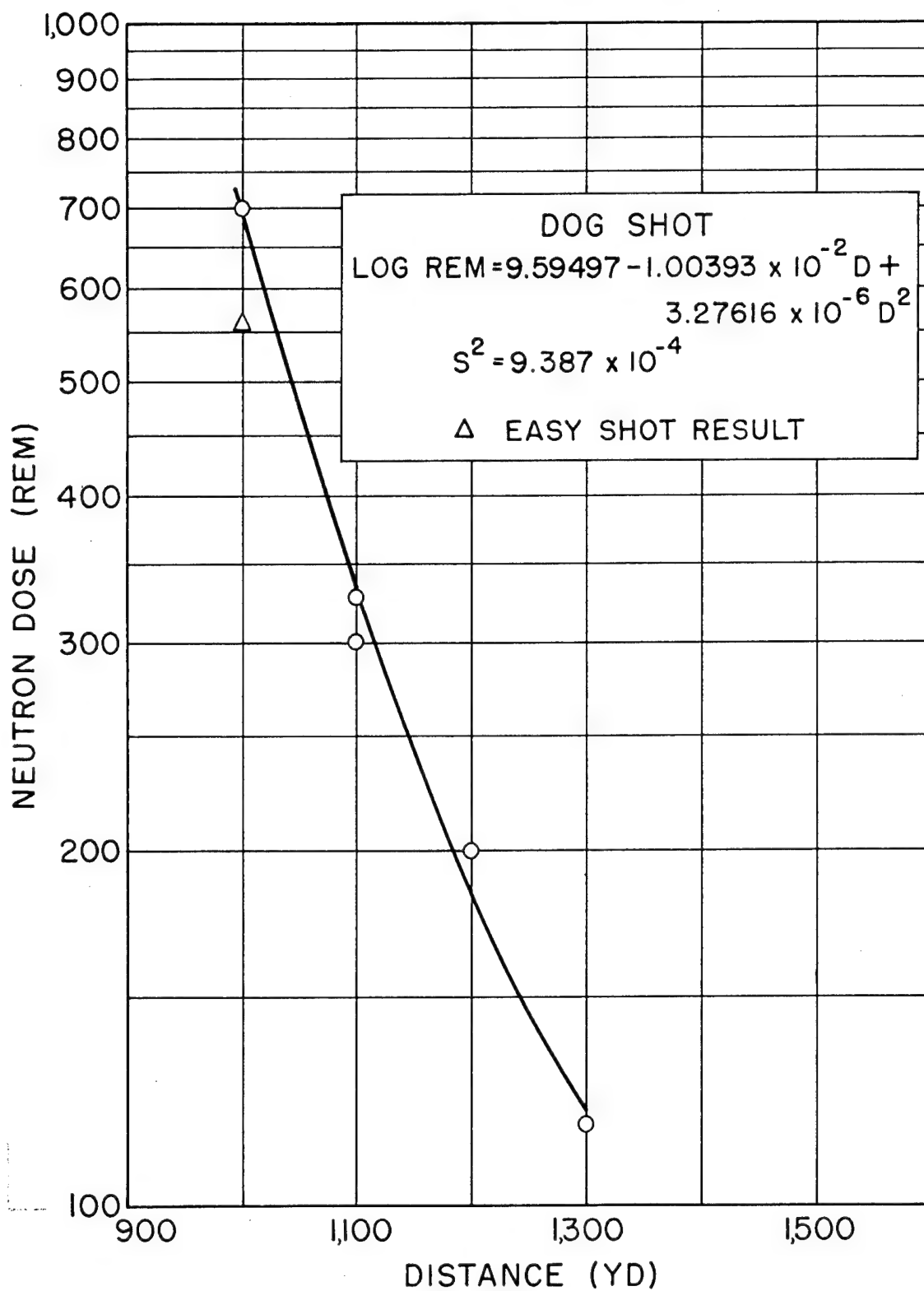
FIG. 5.1 Total Neutron Dose in rem as a Function of Distance from Ground Zero, Dog Shot
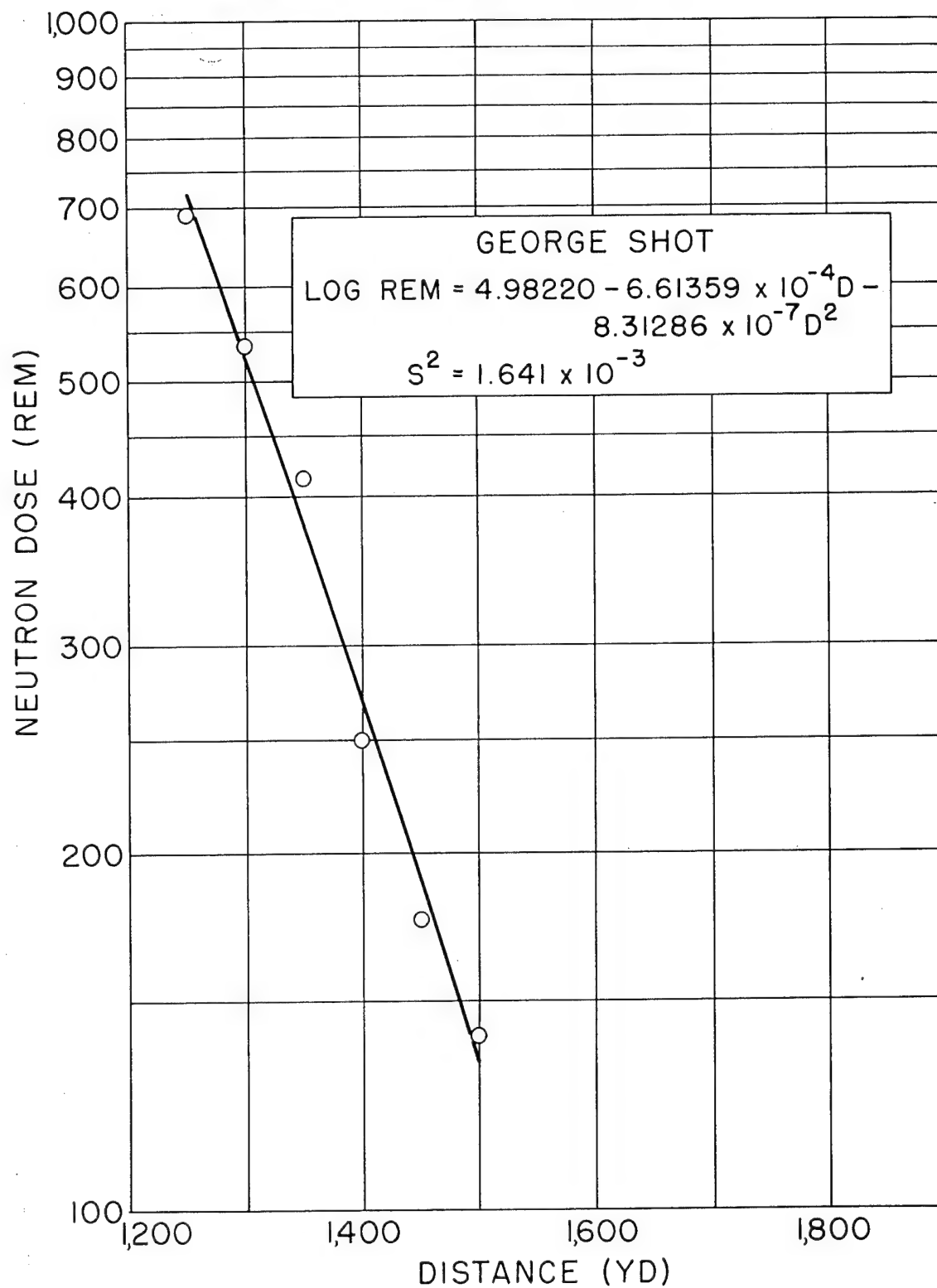
FIG. 5.2   Total Neutron Dose in rem as a Function of Distance from Ground Zero, George Shot

GEORGE SHOT

$$LOG\ REM = 4.98220 - 6.61359 \times 10^{-4}D - 8.31286 \times 10^{-7}D^2$$

$$S^2 = 1.641 \times 10^{-3}$$
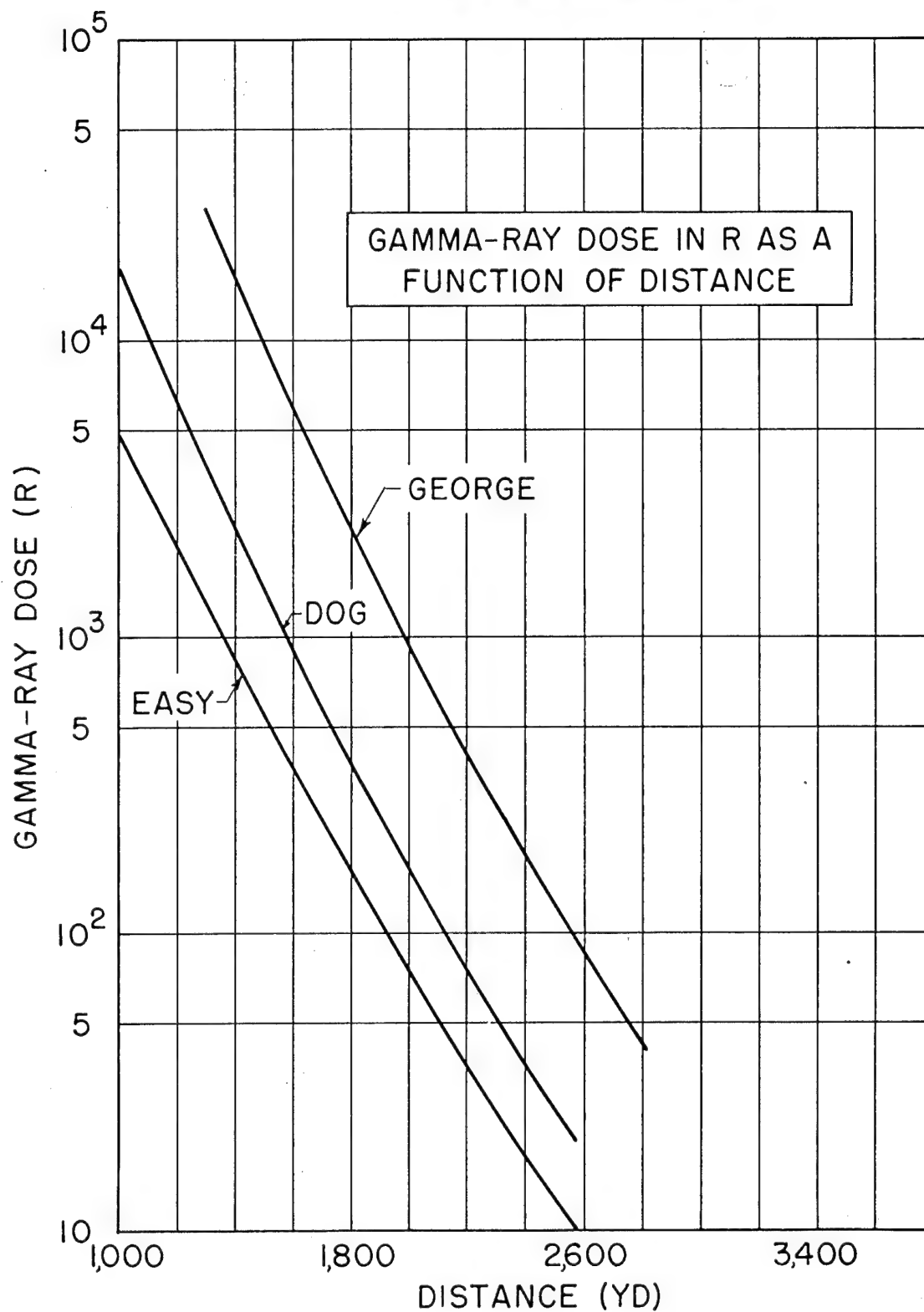
FIG. 5.3 Gamma-ray Dose in Roentgens as a Function of Distance from Ground Zero for Dog, Easy, and George Shots (from NBS data)
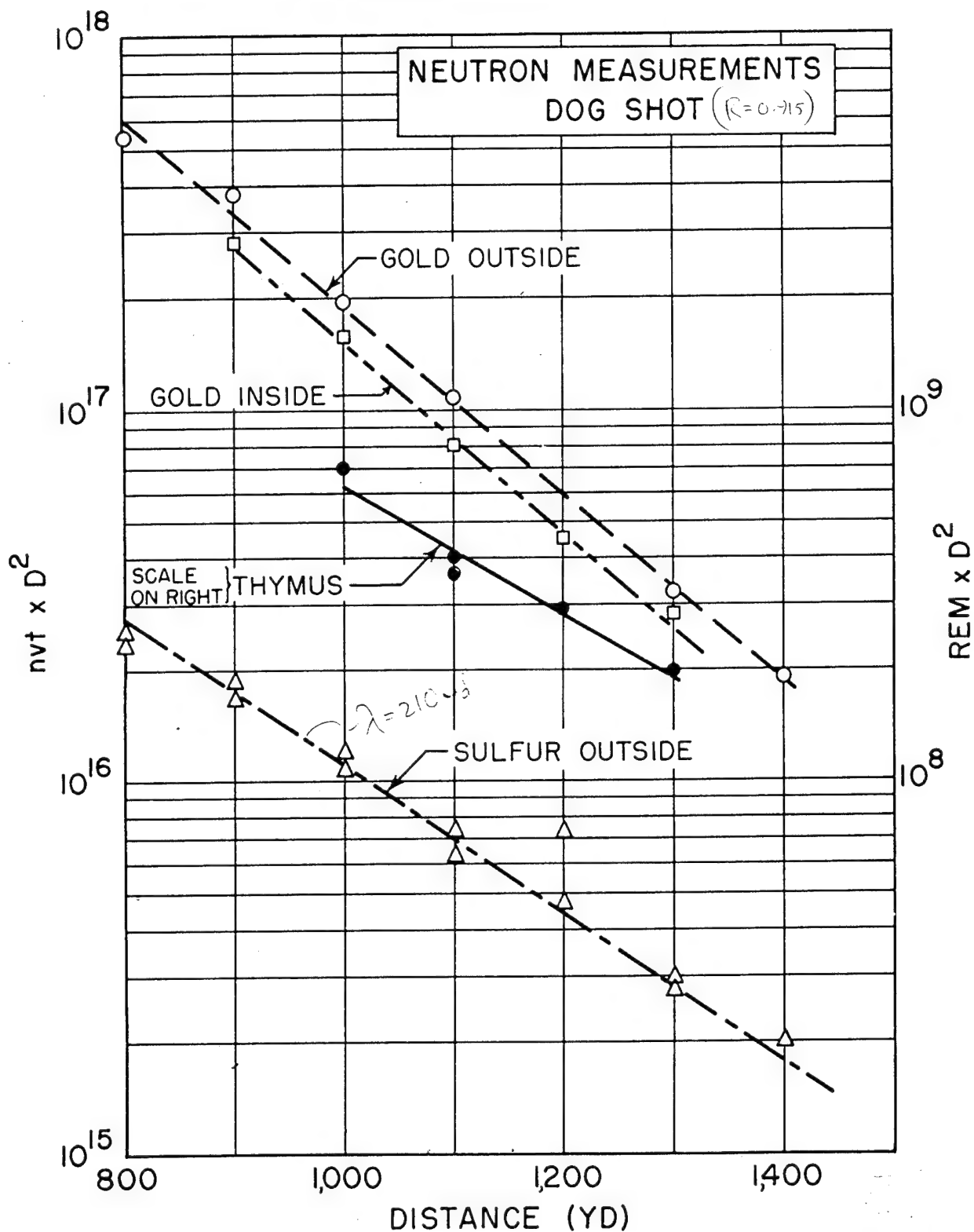
FIG. 5.4 Neutron Flux and Neutron Dose Times (Distance)² Plotted as a Function of Distance, Dog Shot
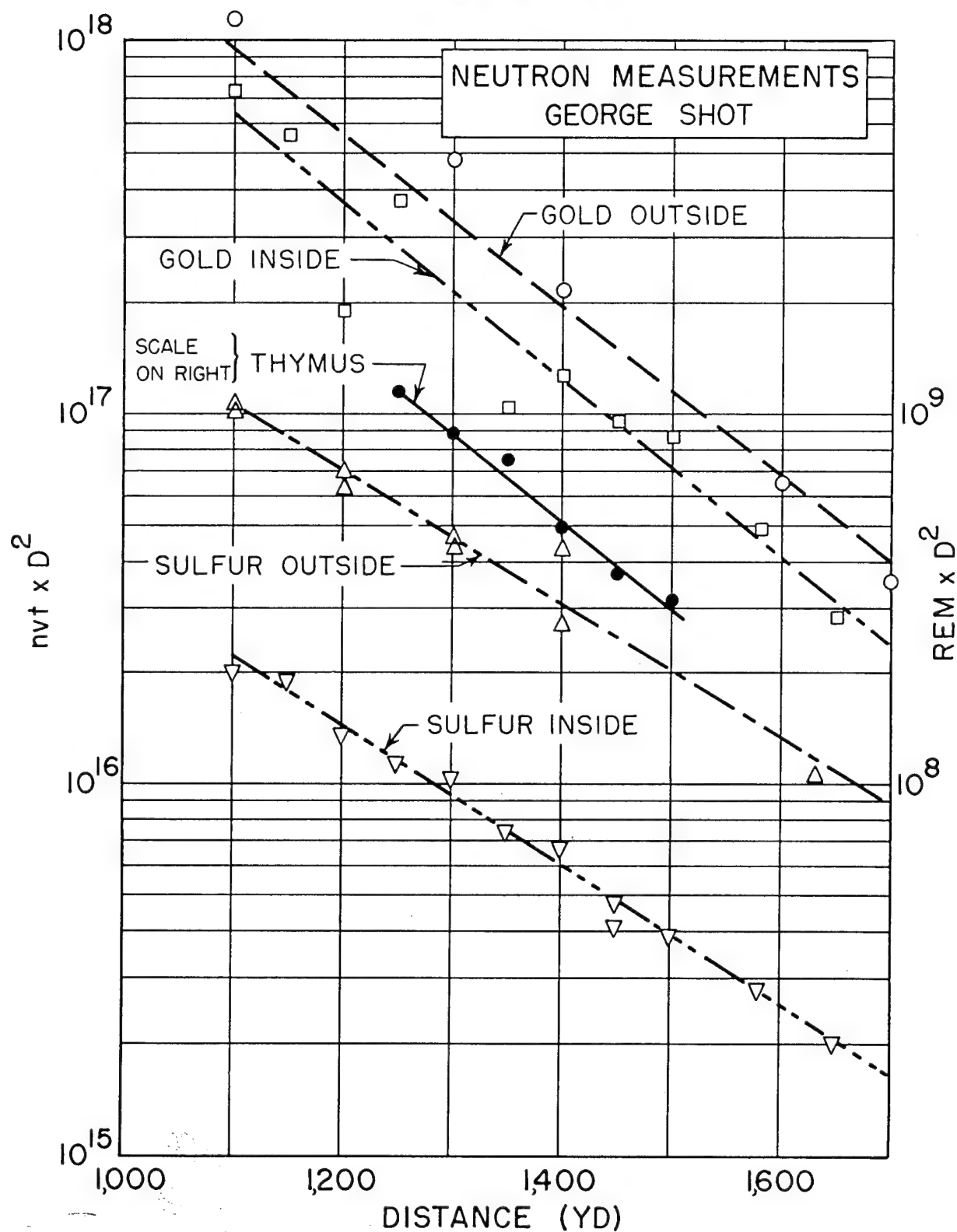
FIG. 5.5 Neutron Flux and Neutron Dose Times (Distance)² Plotted as a Function of Distance, George Shot

Section 3

INVESTIGATION OF THE RADIATION HAZARDS ASSOCIATED WITH PASSAGE THROUGH AN ATOMIC BOMB CLOUD

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Abstract

Mice were flown through the stem of an atomic cloud in well-ventilated cages on drone aircraft in order to investigate the radiation hazards associated with the early passage of aircraft through the cloud. The mice received external radiation doses ranging from a negligible quantity up to 200 r as measured by film-pack and thymic weight loss methods. The acute and chronic hazards due to the inhalation of fission products and plutonium were shown to be negligible in comparison with the external gamma-radiation doses.

Chapter 1

Introduction

At the request of the USAF, experiments were included in Operation Greenhouse to investigate the radiation hazards associated with early passage through the cloud resulting from the detonation of an atomic bomb. These experiments were designed to give information on the relation between the amount of radioactive material taken up and the external dose of gamma radiation received by mice flown through the cloud in well-ventilated cages in drone aircraft. Three groups of mice were placed in each aircraft. Group 1 received only external gamma radiation and was sacrificed 5 days post shot for determination, by the method of thymic weight loss,[1] of the

radiation dose received. Group 2 was exposed both to external gamma radiation and to internal hazard from fission products. This group was sacrificed and analyzed in the same way as group 1. Group 3 received the same exposure as group 2 but was sacrificed 5 hr post shot for radiochemical analysis of fission products contained in the lungs and other organs of the body. No study of the metabolism of the inspired activity was planned. Some data are already available from laboratory studies on the excretion, retention, and distribution of fission products. Furthermore, the ingestion of material retained on the fur of animals used in the field test would make such metabolic studies of doubtful significance.

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[1] Carter *et al.*, Part I, Sec. 1, Chap. 4, of this report.

Chapter 2

Basic Theory

2.1 PREDICTION OF EXPOSURE USING SANDSTONE DATA

Data were obtained at Sandstone [1] on the ratio of gamma intensity inside drone aircraft to fission-product activity caught in the drone's filters as a function of altitude, but not as a function of time after burst. These data are given in Table 2.1 in a recalculated form. Columns 2, 5, and 8 give the intensity of radiation in roentgens (as estimated from film-badge darkening) at various altitudes for the three Sandstone shots. Columns 3, 6, and 9 give the number of fissions found in the filters of the same drone aircraft, and columns 5, 7, and 10 give the ratio of fissions in the filters to gamma radiation. While the data scatter badly and there is no correlation of this ratio with altitude, the average seems to

[1] Sandstone Report, Annex 9, Vol. 30, Part III.

be 10^{12} fissions collected in the filter per roentgen received by the film badges. The ratio ranges from 0.1×10^{12} to 3×10^{12}. It is to be noted that the drones for the Zebra Shot passed through the mushroom while the drones used during X-ray and Yoke Shots traversed the stem. Although Zebra was a much smaller shot (18 kt vs 36 and 49 kt for X-ray and Yoke), both the gamma and fission-product exposures were much higher due to the fact that the aircraft traversed a different part of the cloud. It is interesting that there is no marked alteration in the ratio under the different conditions.

The filters had an air flow of 1,200 cu ft/min or 3×10^7 cc/min. The respiratory minute volume of the mouse is about 100 cc, so that, assuming complete retention in both cases, a mouse breathing air from the cloud should acquire 4×10^{-6} times the amount of fission products found in the filters. The ratio of fis-

TABLE 2.1 GAMMA INTENSITY REGISTERED BY FILM BADGES INSIDE DRONE AIRCRAFT AND FISSION-PRODUCT ACTIVITY CAUGHT IN FISSION-PRODUCT FILTERS, OPERATION SANDSTONE[a]

DRONE ALTITUDE (10^3 ft)	X RAY—36 KT			YOKE—49 KT			ZEBRA—18 KT		
	Gamma Exposure (r)	Fissions in Filters ($\times 10^{-13}$)	F/r[b] ($\times 10^{-11}$)	Gamma Exposure (r)	Fissions in Filters ($\times 10^{-13}$)	F/r[b] ($\times 10^{-11}$)	Gamma Exposure (r)	Fissions in Filters ($\times 10^{-13}$)	F/r[b] ($\times 10^{-11}$)
14	...	..	..	292	8	3	266	21	7
16	102	..	..	192	15	8	292	38	13
18	298	4	1	148	3	2	428	45	10
20	287	4	2	146	..	..	...	53	..
22	64	11	17	104	35	33	827	34	4
24	68	12	17	146	17	11	585	38	6
26	64	11	17	361	22	6	...	..	..
28	56	18	33	...	44	..	...	..	..
AVERAGE	134	..	15	198	..	11	480	..	8

(a) Recalculated from data in Sandstone Report, Annex 9, Part III.
(b) F/r, ratio of number of fissions in filters to roentgens of gamma radiation registered on film badges inside the aircraft.

sion-product uptake to gamma exposure for the mouse is therefore estimated to be 4×10^6 fissions/r.

Assuming conditions similar to those prevailing at the X-ray and Yoke Tests, it was calculated that Greenhouse mice would receive a gamma dose of the order of 100 r and would inhale the products of 3×10^8 fissions. This fission-product level corresponds approximately to 15 μc at the time of inhalation ($\sim$3.5 min), to 0.2 μc at time of recovery ($\sim$3.5 hr), and to 0.005 μc at time of measurement (4 days). (Radioactive decay is assumed to be the only factor reducing the activity, assuming no physiological elimination.) The Sandstone data suggest that gamma and fission-product exposures might vary together, in which case the ratio of 10^6 fissions/r would be approximately constant at varying total doses.

2.2 MEASUREMENT OF FISSION-PRODUCT UPTAKE

2.2.1 Composition and Decay of Fission-product Mixture

A complete analysis of the composition of the fission-product mixture and of the growth and decay of the component nuclides has been given by Hunter and Ballou.[2] On the basis of their data the main components of the mixture and their relative importance at 2 days and at 7 days post-shot time are given in Table 2.2. The activity given in this table is calculated on the assumption of the inhalation of the products of 3×10^8 fissions.

[2] H. F. Hunter and N. E. Ballou, "Simultaneous Slow Neutron Fission of U^{235} Atoms. I—Individual and Total Rates of Decay of the Fission Products," ADC–65. (Note: Although these data are calculated for U^{235}, they will apply with sufficient accuracy to Pu^{239} also.)

TABLE 2.2 CHARACTERISTICS OF FISSION PRODUCTS OF MAJOR IMPORTANCE A FEW DAYS AFTER PRODUCTION

NUCLIDE	ACTIVITY (disintegrations per minute)[a]		HALF LIFE	RADIATION ENERGY (Mev)	REMARKS
	2 days	7 days			
Ce^{143}	2,100	170	33 hr	β1.36 γ0.5	Inhaled as 19-min Sr^{143}
I^{133}	1,800	42	22 hr	β1.35	See also I^{132} below
I^{131}	480	330	8 days	γ0.55	Inhaled as 60-min Te^{133} and 25-min Te^{131}
Zr^{97}	1,740	13	17 hr	β2.1 γ0.8	All ancestors short-lived
Cb^{97}	1,900	14	75 min	β1.4 γ0.8	Short-lived daughter of Zr^{97}; chemistry is very similar
Te^{132}	1,100	360	77 hr	β0.3 γ0.2	From 5-min Sb^{132}
I^{132}	1,140	390	2.4 hr	β1.0, 2.1 γ0.6, 1.4	Short-lived daughter of Te^{132}
Mo^{99}	1,800	540	67 hr	β0.24, 1.3 γ0.24, 0.8	A "standard" fission product; head of chain
Xe^{133}	870	660	5.3 days	β0.34 γ0.08	Daughter of 22-hr I^{133}
Xe^{135}	1,720	. . .	9.2 hr	β0.93 γ0.24	Daughter of 6.7-hr I^{135}
Sr^{91}	630	. . .	9.7 hr	β1.3, 3.2 γ1.3	Short-lived ancestors
Y^{93}	750	. . .	10 hr	β3.1 γ0.7	Daughter of 7-min Sr^{93}
Ba^{140}	630	480	12.8 days	β0.4, 1.05 γ0.14, 0.53	Short-lived ancestors
Sr^{89}	123	114	55 days	β1.50	15-min Rb^{89} parent

[a] Assuming 3×10^8 fissions.

Conversion of tne counting data to number of fissions is possible only if measurements are made on individual nuclides of known characteristics and fission yield. The nuclide of choice for such a measurement was Mo^{99} since it has been extensively studied in connection with bomb efficiency measurements. It has the further advantage of offering a high disintegration rate if samples are measured early. In order to provide a cross check, it was desirable that more than one activity be measured and Ba^{140} and Sr^{89} were chosen for this purpose. These have a lower activity initially, but on the other hand, their longer half lives permit the measurements to be made at a later date. Both are well-known nuclides with easily measurable radiations and well-established fission yields. The more difficult chemistry of elements such as Ce, Zr, Cb, and Te made them less desirable for this experiment. Measurements were also made on the whole thyroids, animal metabolism in this case providing the chemical separation of nearly pure iodine activities. From the known fission yield [3] and the observed activity of a given fission product the fraction of the total number of fissions may be calculated.

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[3] Sandstone Report, Annex 9, Vol. 30, Part III.

2.2.2 Metabolic Translocation

It was desired to measure the number of fissions, the products of which were taken into the lungs of the test animals, independent of any later physiological effects of elimination and translocation. Since a small amount of translocation was expected, measurements were made on lungs, GI tract, skin, bones, thyroid, and remains. The animals were sacrificed as soon as possible after the return of the aircraft. The time of sacrifice was about 5 hr after shot time. Most of the time interval before sacrifice was spent at altitude while the drone aircraft was waiting its turn to land. It was expected that the animals would be inactive due to the low temperature prevailing, and effects such as the ingestion of material retained on the fur would be minimized. However, the unexpectedly high temperatures encountered at altitude in the field resulted in considerable activity of the animals and large quantities of fission products were ingested by the licking of fur. There was no simple expedient to prevent such ingestion. The ratio of ingested to inhaled material wás so much higher than anticipated that quantitative interpretation of the data is difficult except to establish upper limits.

Chapter 3

Experimental Methods

3.1 RADIATION DOSE MEASUREMENTS

3.1.1 Thymic Weight Loss Method

A determination of the 250–KVP X-ray equivalents of the doses received by the mice was made by the thymic weight loss method. This procedure is reported elsewhere.[1] Splenic weight loss could not be used for dose measurement because of the low doses encountered in the aircraft.

Both special and general control groups were kept. The general control groups never left the animal quarters on Japtan Island. The special control groups were flown during the dress rehearsal preceding each shot. In so far as possible, the time at altitude and other conditions exactly paralleled the conditions during the actual shots.

3.1.2 Film-pack Method

Film packs were supplied and analyzed by the NBS. The doses given carry a probable error of ±20 per cent. All film packs were covered with 0.845 cm of bakelite, 0.107 cm of tin, and 0.033 cm of lead. The lead covering was on the outside and the bakelite was on the inside, next to the film. This gives a total shielding of 2.32 g/cm².

3.2 FISSION-PRODUCT MEASURE-MENTS

3.2.1 Measuring Equipment

Radioactivity measurements were carried out using a Tracerlab Autoscaler and a thin (1.6 mg/cm²) mica-window counter tube.

3.2.2 Chemical Analyses

The chemical procedures used were modifications of those outlined by Meinke.[2]

3.2.3 Carrier Recovery Experiments

Experiments were performed to test the yield of the analytical procedures. Solutions containing 10 mg each of Mo, Sr, and Ba were mixed and subjected to chemical analysis. Recovery in the final precipitation is shown in Table 3.1. Quantitative yields are not to be expected since the procedures are chosen principally on the basis of degree of decontamination. Lack of 100 per cent recovery does not affect the accuracy of the radiochemical analyses since known amounts of carrier are added to the tissue to be analyzed for the purpose of establishing the over-all recovery of the radioisotope.

Table 3.2 presents the results of experiments in which 10 mg each of Mo, Sr, and Ba carrier were added to various excised mouse organs before ashing and the entire procedure carried out. Samples labeled "A" were ashed without addition of concentrated HNO₃; samples "B" were ashed in the presence of HNO₃. A significant increase in recovery was obtained by the latter method.

3.2.4 Preliminary Animal Experiments

Experiments were performed in which fission-product mixtures containing known amounts of Mo, Sr, and Ba activities were injected intravenously into mice. The animals were sacrificed after 4 hr and selected organs analyzed. Results are shown in Table 3.3.

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[1] Carter *et al.*, Part I, Sec. 1, Chap. 4, of this report.

[2] W. Wayne Meinke, "Chemical Procedures Used in Bombardment Work at Berkeley," AECD–2738 (UCRL–432).

TABLE 3.1 RESULTS OF RECOVERY OF CARRIER FROM SOLUTION IN SIX SEPARATE EXPERIMENTS

Mo (per cent)	Ba (per cent)	Sr (per cent)
84.8	66.8	91.9
84.0	65.2	69.2
87.3	55.1	78.3
88.6	53.4	81.4
88.6	76.4	76.0
88.4	52.8	88.7

TABLE 3.2 RECOVERY OF CARRIER FROM MOUSE TISSUE

ORGAN	Mo (per cent)	Ba (per cent)	Sr (per cent)
Liver A	49.3	13.6	22.6
B	64.6	45.1	53.8
Lungs A	68.4	31.5	44.3
B	89.4	62.5	57.9
Kidney A	76.1	41.3	50.2
B	85.3	53.3	55.7

TABLE 3.3 RECOVERY OF FISSION PRODUCTS INJECTED INTRAVENOUSLY INTO THE MOUSE

ANIMAL	ELEMENT	ORGAN	WEIGHT OF PPT	ACTIVITY (c/s)	RECOVERY FACTOR[a]	CORRECTED ACTIVITY (c/s)	RECOVERY (per cent)
1	Mo	Inj. sol.	37.1	169.5	1.056	179.0	....
		Liver	12.2	37.4	3.210	120.2	67.2
		GI tract	21.7	29.8	1.805	53.8	30.1
		Feces	34.3	1.27	1.142	1.45	0.8
						Total	98.1
2	Mo	Liver	38.9	37.7	1.007	38.0	21.2
		GI tract	18.2	13.3	2.152	28.6	16.0
		Feces	26.4	1.0	1.483	1.5	0.8
						Total	38.0
1	Ba	Inj. sol.	13.0	125.5	1.415	177.5	....
		Liver	5.5	6.5	3.345	21.7	12.2
		GI tract	4.1	10.8	4.488	48.5	27.3
		Feces	12.1	8.3	1.521	12.6	7.1
						Total	46.6
2	Ba	Liver	5.4	4.6	3.407	15.5	8.8
		GI tract	4.8	15.6	3.833	59.8	33.7
		Feces	9.1	1.4	2.022	2.9	1.6
						Total	44.1
1	Sr	Inj. sol.	15.7	53.0	1.408	77.6	....
		Liver	9.5	2.8	2.326	6.4	8.6
		GI tract	5.1	3.4	4.333	14.6	19.6
		Feces	18.8	3.2	1.176	3.7	5.0
						Total	33.2
2	Sr	Liver	8.6	2.92	2.570	11.7	15.7
		GI tract	10.7	9.79	2.065	20.2	27.1
		Feces	23.0	0.79	1.0	0.8	1.1
						Total	43.9

[a] The reciprocal of the fraction of inert carrier recovered.

The "recovery factor" is the correction applied to the observed activity on the basis of the recovery of the inert carrier which was added just before ashing.

3.3 FIELD EXPOSURE CONDITIONS

Three compartments of approximately 1,000 cu in. each were constructed in the waist of each drone aircraft and ventilated by means of an air scoop which extended into the airstream outside the aircraft. Thirty mice were placed in a ¼-in.-mesh wire cage in each of the compartments of the drones flying at 16,000, 18,000, and 20,000 ft on Dog, Easy, and George Shots. Compartment 1 of each aircraft was ventilated at the rate of 1,000 cu in./min by filters which removed radioactive particles so that the mice therein received only gamma radiation. Compartments 2 and 3 of each aircraft were ventilated at the rate of 6,000 cu in./min with unfiltered air so that the mice therein received gamma radiation plus exposure to fission products. The mice were placed in the compartments at the time of start of engines for take-off, which was about 4 hr before detonation. The cages and mice in compartments 1 showed little or no radioactivity upon removal indicating efficient removal of fission products from the air passing through the filters. Mice and cages in compartments 2 and 3 were contaminated with fission products from the cloud. Mice from compartment 3 were killed by chloroform inhalation within 1 hr after removal from the aircraft, frozen, placed on dry ice, and returned to the ZI on the H+10 hr plane for fission-product analysis of various organs. Mice from compartments 1 and 2 were returned to the animal quarters on Japtan Island and sacrificed on the 5th day post shot for thymus weight loss analysis.

The first pass through the cloud occurred 3 to 4 min after detonation. A second pass followed about 10 to 12 min after detonation. It is very likely that the first pass accounted for almost all of the radiation dose received. All passes were through the stem of the cloud.

Chapter 4

Experimental Results

The amounts of fission products found in various organs of the mice exposed in compartment 3 and sacrificed at approximately H+5 hr are given in Table 4.1. The numerical values in the table are calculated from each of the three individual measurements, Ba, Sr, and Mo, as well as from a measurement of the gross activity without any chemical separations and from iodine activities concentrated by the thyroid. All data in this table are expressed in terms of the number of fissions required to produce the activity measured. For this reason the four measurements (*i.e.*, total, Mo, Ba, and Sr) made on each organ should give identical results if there were no fractionation of the activities in the cloud nor in the animal after uptake. The actual scatter of the data are a result of variations caused by these effects.

The equivalent radiation dose of 250–KVP X radiation as determined by thymic weight loss for mice exposed to gamma radiation in compartment 1 and to gamma radiation plus inhalation of fission products in compartment 2 is given in Table 4.2. (Mice in both compartments 1 and 2 received filtered air on Dog Shot.) Film-badge readings from NBS film packs placed in the compartments with the mice are compared with the thymic results.

TABLE 4.1   ACTIVITY FOUND IN MICE FLOWN IN DRONE AIRCRAFT
(Expressed in Units of 10^3 fissions/mouse)

| ORGAN | NUCLIDE | GREENHOUSE SHOTS AND DRONE ALTITUDES (10^3 ft) | | | | | | | | |
| | | Dog | | | Easy | | | George | | |
		16	18	20	16	18	20	16	18	20
Lungs	Total	0.1	0.1	0.1	0.07	0.1	0.3	<0.01	<0.01	<0.01
	Mo	0.05	0.08	0.1	0.02	0.08	0.2	<0.01	<0.01	<0.01
	Ba	0.02	0.01	0.03	0.01	0.02	0.04	<0.01	<0.01	<0.01
	Sr	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Skin	Total	6	12	29	15	66	110	0.2	0.4	12
	Mo	2	5	14	2	12	72	0.3	0.4	0.4
	Ba	3	6	7	2	7	51	0.7	0.8	21
	Sr	3	4	3	1	8	10	0.2	0.2	135
GI tract	Total	7	10	29	4	33	51	0.6	0.7	7
	Mo	6	9	11	3	12	33	0.04	0.05	0.3
	Ba	3	4	6	2	15	19	1.0	1.2	22
	Sr	<0.01	<0.01	<0.01	0.8	7	5	0.07	0.1	48
Remains	Total	0.6	2	5	0.9	3	6	<0.01	0.2	0.7
	Mo	0.2	1.5	4	0.4	1.3	3	<0.01	<0.01	0.02
	Ba	0.5	0.7	1.3	0.4	1.2	3	0.1	0.2	1.1
	Sr	0.2	0.2	0.3	0.2	0.5	0.8	<0.01	<0.01	<0.01
Skeleton	Total	1.8	3.6	5.1	0.7	3.6	13	0.03	0.1	0.4
Thyroid	I^{131}	0.03	0.02	0.02	0.03	0.2	0.2	<0.01	<0.01	0.01
	I^{133}	0.1	0.1	0.1	0.1	0.5	0.5	<0.01	<0.01	0.01

TABLE 4.2 EQUIVALENT DOSE OF 250-KVP X RADIATION RECEIVED BY MICE IN DRONE AIRCRAFT FLOWN THROUGH THE STEM OF THE CLOUD 3 TO 4 MIN AFTER DETONATION

SHOT	DRONE ALTITUDE (10^3 ft)	EQUIVALENT (250-KVP X RAY) RADIATION DOSE RECEIVED BY MICE AS INDICATED BY THYMUS WEIGHT LOSS (r)		FILM-BADGE READING (r)[a]	RATIO OF COLUMNS 4 TO 5
		Gamma+ Fission Products	Gamma Radiation Only		
Dog	20	....	188	84.5	2.2
Dog	20	....	142	80.0	1.8
Dog	18	....	129	65.7	2.0
Dog	18	....	102	61.8	1.7
Dog	16	....	156	112	1.4
Dog	16	....	118	104	1.1
Easy	20	220	171	135	1.3
Easy	18	137	79	54.0	1.5
Easy	16	<75	<75	25.5	
George	20	<75	120	....	
George	18	75	87	....	
George	16	<75	<75	4.5	

[a] Film-badge data supplied by NBS.

Chapter 5

Discussion

The very large amounts of activity found on the skin and in the GI tract (Table 4.1) of these mice indicate that ingestion was the predominant mode of entry of the activity.

Regardless of the mode of entry, the highest activity levels observed can be shown to be sufficiently small so as to result in a negligible hazard compared with the dose of gamma radiation from the cloud. The total energy released from a mixture of fission products as a function of time is given by:

$$B(t) + \Gamma(t) = 5.6t^{-1.26} \qquad (5.1)$$

where $B(t)$ is the average beta energy per disintegration, $\Gamma(t)$ is the average gamma energy per disintegration, and t is the time since fission in seconds, the energy being in units of million electron volts per second per fission. (This is an experimental result obtained by L. B. Borst for the period from 20 min to 3 days. Similar results are obtained using the Way-Wigner theoretical equation.)[1] Figure 5.1 is a plot of the cumulative dose as a function of time for a concentration of the products of 10^8 fissions/g of tissue on the basis of Eq. 5.1. This corresponds to the products of 30×10^8 fissions in an average mouse. Uniform distribution of the activity is assumed. Table 4.1 shows that even if all the activity found in the GI tract and remains had been inhaled rather than ingested, the total dose to the animal assuming uniform distribution would barely exceed 10 rep even in the worst case. Since it appears that actually only a small percentage of this activity was inhaled and since no metabolic elimination has been considered, it is safe to conclude that the dose which the whole body would have received from inhaled material alone is less than 1 r. Taking the largest amount of fission products found in the lungs (3×10^7 for Easy Shot, 20,000 ft) and assuming that there was no physiological elimination or translocation, the radiation dose to the lungs is calculated to be 10 r. Since these doses are considerably smaller than external gamma-radiation doses, it would seem that the acute hazard from inhaled activity is negligible in connection with the passage of an aircraft through an atomic cloud shortly after bomb detonation.

Another interesting conclusion can be drawn from Fig. 5.1. It is apparent that even assuming no metabolic elimination, the major portion of the dose from a fission-product mixture is received during the first few days. If the insoluble particle problem is not considered, the possibility of the fission products constituting a chronic hazard is eliminated by the following considerations. Assume:

1. That man, because of his greater respiratory minute volume, takes up 200 times as much fission products as a mouse. On the basis of the maximum total amount found in any of the mice a man might take up 10^{12} fissions.

2. That there is no metabolic elimination of the activity but only radioactive decay. This results in a total activity of 0.1 μc remaining in the man after 1 yr.

3. That all this residual activity is as dangerous as Sr^{90}. Actually, the residual activity is much less dangerous because at this time the major fission-product activities are much shorter lived than Sr^{90}.

[1] H. F. Hunter and N. E. Ballou, "Simultaneous Slow Neutron Fission of U^{235} Atoms. I—Individual and Total Rates of Decay of the Fission Products," ADC–65.

The estimated safe dose of Sr^{90} fixed in the body was recommended by the Chalk River Conference to be 0.5 μc. The chronic hazard from fission products taken up by man in passage through an atomic cloud is seen to be only one-fifth of this value, even under the pessimistic assumptions made above. This indicates that inhalation of fission products within a short period of time after bomb detonation does not constitute a long-term danger.

From the amount of fission products found in the mice, it is calculated that each mouse retained about 10^{-16} of the total bomb products. Assuming a human respiratory minute volume 200 times that of the mouse, a man might be expected to retain 2×10^{-14} of the bomb. Assuming the cloud to contain 10^4 g of unreacted plutonium, it is apparent that a man might take up as much as 2×10^{-4} μg. When this is compared with the official tentative safe dose of plutonium of 0.5 μg accepted by the Division of Biology and Medicine, AEC, it appears negligible. If one ignores the unevaluated problem of insoluble particles in the lung, the unreacted plutonium inhalation in passage through an atomic cloud does not constitute a hazard.

It is to be noted that in the evaluation of the hazard due to inhalation of fission products and unreacted plutonium the unevaluated problem of the insoluble particle has not been considered. The point in question is whether or not the intense, but extremely localized, ionization in the immediate vicinity of an insoluble fixed radioactive particle constitutes a disproportionate hazard. This question is highly controversial at present and no conclusive experiments have been performed. While evidence of the absolute magnitude of this hazard is lacking, it is the opinion of the authors that it is negligible in comparison with the external gamma-radiation hazard from passage through the cloud at short times after detonation. A theoretical treatment of the insoluble particle problem is given by K. Z. Morgan.[2]

Landahl's[3] recent detailed theoretical analysis of the hazards resulting from passage through an atomic cloud reaches the same conclusions as those presented in this report, namely, that inhaled activity results in a dose negligible compared with external gamma radiation.

The thymic weight loss method used to determine the equivalent dose presented in Table 4.2 is discussed in detail elsewhere.[4] In the range of total radiation dose of 75 to 200 r a precision of ±20 per cent may be expected. The results obtained in the ground hemispheres[5] indicate that the film-badge and thymic weight loss methods may be expected to agree within this limit of error where only hard gamma radiation is involved. By comparing columns 4 and 5 of Table 4.2 it can be seen that there is a significant difference between the radiation dose indicated by the film-pack method vs the thymic weight loss method in the cloud. Since the film pack was shielded by 2.32 g/cm^2 the difference noted between the two methods of dose measurement would seem to indicate the presence in the cloud of a radiation which is highly attenuated in the shielding, but capable of producing radiation damage in the mouse.

A comparison of columns 3 and 4 of Table 4.2 shows that the radiation dose from external gamma radiation plus that from uptake of fission products does not differ significantly from the gamma-radiation dose alone. This is to be expected in view of the precision of the method for measurement of radiation dose in this range and confirms conclusions reached in the discussion of Table 4.1.

Total radiation doses to the mice range from a negligible amount up to about 200 r. These results are of course applicable only to the specific conditions of the experiment.

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[2] Karl Z. Morgan, "An Estimate of the Exposure from Specks of Insoluble Radioactive Material That May Become Lodged in the Lungs," CF–48–8–86, August 1948.

[3] H. D. Landahl, "Calculations of the Hazard Involved in a Passage through a Radioactive Cloud Resulting from a Nominal Atomic Bomb."

[4] Carter *et al.*, Part I, Sec. 1, Chap. 4, of this report.

[5] *Ibid.*

Chapter 6

Conclusions

1. Mice exposed in ventilated cages in drone aircraft flying through the stem of an atomic cloud at 16,000 to 20,000 ft 3 to 4 min after detonation took up in the body the products of approximately 10^9 fissions.

2. The ratio of the activity found in the lungs of the exposed mice to that in the GI tract was about 1 to 100, which indicates that most of the activity found in the animals was ingested.

3. The total amount of fission-product activity found in the mice due to ingestion as well as inhalation corresponds to an acute radiation dose of not more than 10 rep if uniformly distributed.

4. The amount of fission-product activity found in the lungs of the mice corresponds to an acute radiation dose to the lungs of not more than 10 rep if uniformly distributed in the lungs.

5. Inhalation of the unfractionated mixture of fission products at short periods of time after detonation does not constitute a chronic hazard.

6. At short periods of time after detonation, inhalation of unreacted plutonium from the cloud of a successful bomb detonation constitutes a negligible hazard compared to fission-product inhalation and external gamma radiation.

7. Even in a completely ventilated aircraft the radiation exposure due to inhaled fission products is small compared with the exposure due to external gamma radiation.

8. It appears that the external radiation received by the mice may contain an appreciable fraction of a soft component.

9. The total radiation dose received by the mice under the conditions of these experiments ranged from a negligible quantity up to approximately 200 r.
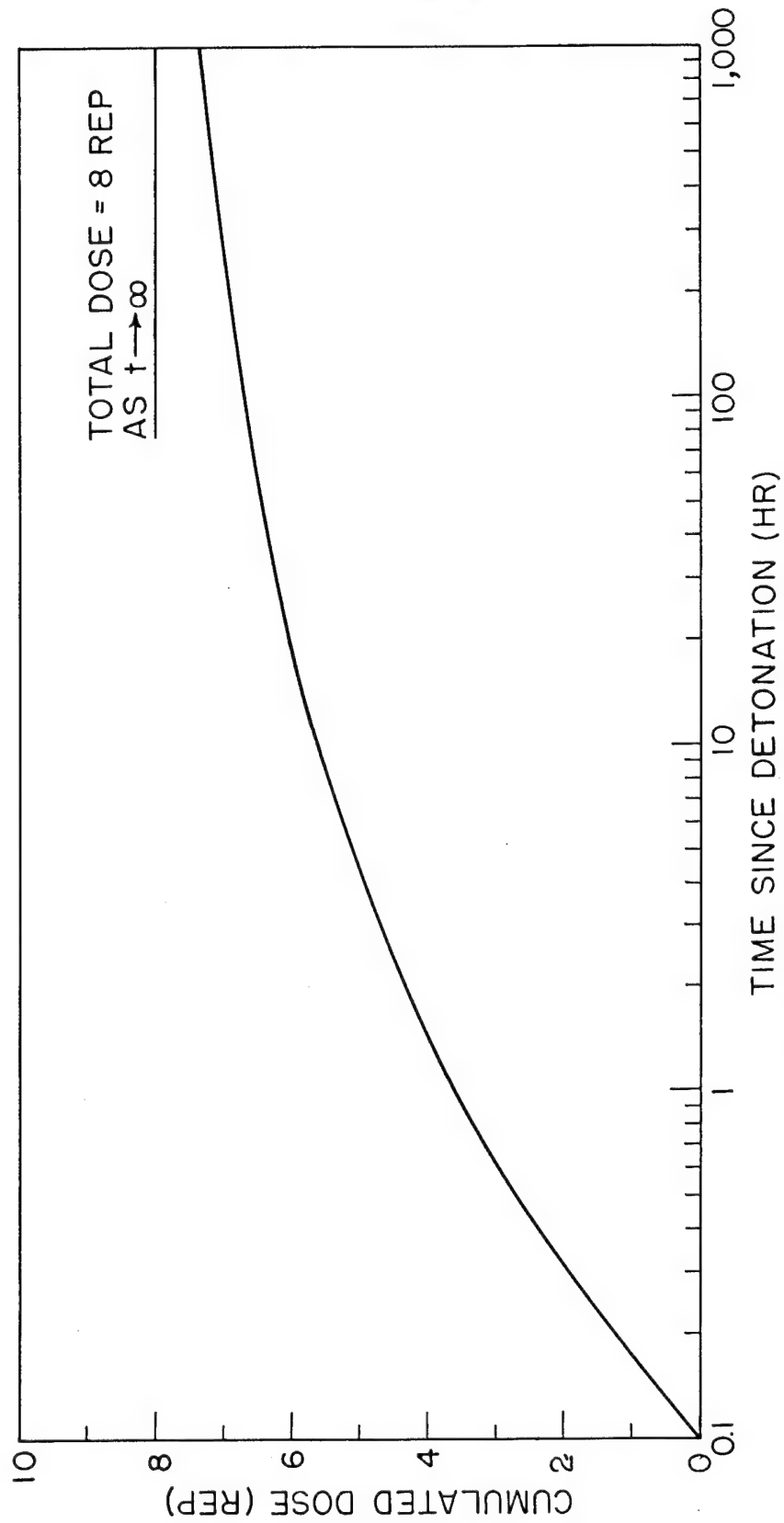
Fig. 5.1 Cumulative Dose for Inhalation of 10^8 fissions/g

TOTAL DOSE = 8 REP
AS $t \rightarrow \infty$

TIME SINCE DETONATION (HR)

CUMULATED DOSE (REP)

Part II

DEPTH DOSIMETRY IN UNIT-DENSITY MATERIALS

by

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Acknowledgments

Abstract

Field measurements of biologically significant characteristics of gamma radiation from atomic bomb tests at Operation Greenhouse are presented. Depth-dose measurements in media of approximately unit density were made, using ionization chambers of high electrical saturation and essentially flat wave-length response.

Absorption curves at three different distances from two different shots indicate a constant value of radiation quality within the limits considered, these limits having been chosen to include the dose range near absolute probable lethality.

Comparative evaluation of depth-dose readings with various simulated sources indicate that a satisfactory laboratory equivalent to the gamma component of bomb radiation is offered by the 10-Mev betatron.

Chapter 1

Introduction[1]

1.1 OBJECTIVE

The objective of this experiment was to apply the techniques of radiology and radiation therapy, modified as necessary, to determine the quality of the gamma radiation from several atomic explosions, to measure the dose at various distances, and to investigate the possibility of reproducing the gamma-ray effects of the bomb in the laboratory.

1.2 HISTORICAL BACKGROUND

Since the time when it became evident that ionizing radiation influenced living tissue, clinical radiologists and radiation physicists have been working to improve the techniques employed in evaluating the biological effects of radiation. An excellent paper by Quimby[2] gives a history of this valuable work.

It was realized very early that the effects of gamma and X radiation on tissue depended upon the quality (wave length) of the radiation as well as the quantity. Investigators immediately began to look for a means of measuring the amount of radiation received at various depths in the body. It was not practical to measure the depth doses directly in the patient, so a substitute had to be found. Since tissue consists predominantly of water, it was decided that measurements could be made at various depths in a water bath and that the values would be approximately the same as if they were made in the tissue itself. This water bath came to be known as a phan-

tom. It was not always convenient to use water for depth-dose measurements; so the suitability of other substances was investigated and it was found that pressed wood or masonite could be used as a substitute if its density did not vary from unity by more than 3 per cent. Spiers[3] has presented a rather comprehensive analysis of the characteristics of materials commonly used in phantoms for radiation measurement.

The use of suitable detectors and phantom materials has made it possible to estimate what effect various quantities and qualities of radiations will have at different depths in the body.

1.3 BASIC PRINCIPLES INVOLVED

When a monochromatic beam of gamma or X radiation interacts with a scattering medium, there will be quanta present of varying wave lengths due to the Compton effect. Individual quanta may have been scattered more than once in traversing the medium, so the single wave length will have gradually disappeared and been replaced by a broad band of wave lengths extending away on the long wave-length side of the primary radiation. Since as a general rule the primary beam itself is not monochromatic, the spectral distribution at various points within the medium becomes even more complex.

When this complex spectral distribution is superimposed on the scattering phenomena; filtration effects, which tend to eliminate the longer wave lengths from both the primary and secondary radiation, are also introduced. The two sets of phenomena are acting in oppo-

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[1] This report is also listed as Naval Medical Research Institute Report NM 006 012.06.01.

[2] Edith H. Quimby, "The History of Dosimetry in Roentgen Therapy," *The American Journal of Roentgenology and Radium Therapy*, LIV (No. 6) (1945), 686–703.

[3] F. W. Spiers, "Materials for Depth Dose Measurement," *British Journal of Radiology*, XVI (1943), 90.

site directions so far as a resultant effective wave-length change is concerned; therefore, it is possible that a measurement of the quality of the primary beam would give little indication of the nature of the radiation within the scattering mass. Even an absorption curve in approximately unit-density material does not supply the radiologist and radiation physicist with the information he must have to evaluate the dose at various depths in the body, since it does not take into consideration the contribution of secondary scatter from what underlying tissue might exist.

It has, therefore, been the practice in radiology, whenever the effects of a beam of radiation are unknown, to place ionization chambers throughout a unit-density phantom which is irradiated under conditions similar to those used for the patient. These ionization chambers measure the amount of ionization taking place at the various locations in which they were placed. This information allows the radiologist and radiation physicist to calculate the dose received by various parts of the body and to evaluate the effects that might be produced.

Chapter 2

Materials and Methods

2.1 GENERAL DISCUSSION

Four types of phantom were used in this experiment, with one or more of the various types of detector placed in each. The spherical phantoms were made of lucite and contained all three types of detectors: ionization chambers, film, and phosphate glass. The swine, mouse, and tank phantoms were made of masonite and contained only the film except in the case of Dog Shot, when film and ionization chambers were used in the mouse phantoms.

2.2 SPHERICAL PHANTOMS

2.2.1 Information Obtained from the Spheres

Fortunately, a wise choice was made in the early design of this experiment to place the maximum effort on obtaining good data from the spheres. From the data obtained, it should be possible to calculate the absorption coefficient for broad-beam conditions in approximately unit-density material, to determine the equilibrium wall-thickness dose, and to formulate specifications for laboratory equipment that would reproduce the gamma component of bomb effects.

2.2.2 Design of Spheres

The spherical phantoms (Figs. 2.1 and 2.2) were so designed that the detectors in them would measure the integrated dose in approximately 4π geometry. It was necessary to add material for supports however, so in the case of all spheres a constant value of 6 per cent of the surface was used for this purpose. The spheres were made of lucite and each had a central cavity of 5 cm diameter in which to place the detectors. The wall thicknesses surrounding this cavity were 0.6, 1.0, 1.6, 3, 5, 9, and 17.5 cm.

2.2.3 Detectors Used in the Spheres

There were very few ionization chambers available of a suitable type for the experiment, so it was decided that they would be concentrated in the two sphere stations from which the most valuable data (in terms of lethal-dose ranges) were expected to be obtained. Film and phosphate glass were placed in all the spheres at all stations.

A Sievert ionization chamber was found to be the most suitable for use in this experiment. It is 5 mm in diameter and 20 mm long, with a voltage gradient of 11,000 volts per centimeter, and has a practical working range of 50 to 650 r. The leakage is less than 1 per cent in 24 hr and the energy dependence is negligible above 100 kev.

The films used in the spheres were the same as those used in the NBS film pack; however, they did not have the NBS shield around them.

The glass used was of the same composition as the phosphor glass used in the Navy Department Bureau of Ships DT–60 Radiac Detector, but was without the shielding locket. Energy dependence was thus comparable to that of the unshielded NBS film pack.

2.2.4 Control Studies

The spheres were used in pre- and post-test control studies to evaluate the response of the three detectors to various energies in approximately unit-density material. Calibration exposures were made from 50 to 800 r with various X-ray and betatron voltages between 200

KVP and 22 Mev, and also with a large Co^{60} gamma source. In this series each of the three types of detector was exposed, both individually and in conjunction with the other two, in each thickness of sphere.

2.2.5 Method of Exposing Spheres

The spheres were suspended about 2 ft from the ground in such a manner that there would be the least chance of their shadowing each other. For Easy Shot, a complete set of seven spheres was placed at each of the following stations: 81 (900 yd), 80b (1,260 yd), 80c (1,460 yd), 80d (1,645 yd), and 82 (2,270 yd). For George Shot, the stations used were 80c (1,800 yd) and 80d (2,160 yd).

2.3 SWINE PHANTOMS

Swine phantoms were placed in the same type of container and at the same locations as the swine themselves in an attempt to evaluate the dose received throughout the body of such a large animal.

Each swine phantom (Fig. 2.3) was made up of a laminated cylinder of ¼-in. masonite 36 cm long and 36 cm in diameter, capped with laminated hemispheres of 18-cm radius, making the over-all length of the phantom 72 cm.

Although it was realized, after control studies had been made (Fig. 2.4) that the films to be used were not a very satisfactory type of detector for depth-dose measurements, it was decided that they would supply some information of value for future use. Film packs were accordingly distributed throughout each swine phantom (Fig. 2.5).

On Easy Shot, swine phantoms were placed in the same type of container as the swine themselves and in the same locations at Stations 72a (1,400 yd), 72b (1,444 yd), 72c (1,488 yd), 72d (1,532 yd), 72e (1,576 yd), 72f (1,620 yd), 72g (1,655 yd), 72h (1,354 yd), and 72i (1,750 yd). The one exception was a single phantom at Station 81 (900 yd) where there were no swine. On George Shot, swine phantoms were placed at Stations 70f (1,670 yd), 70j (1,710 yd), 70v (1,812 yd), 71d (1,955 yd), and 71f (2,160 yd).

2.4 MOUSE PHANTOMS

Mouse phantoms were placed in the cages with the mice to evaluate the dose received by the mice in various parts of the cage. These consisted of laminated blocks of masonite 2 by 4.5 by 6 cm (Figs. 2.6 and 2.7) with film packs sandwiched between layers.

On Dog Shot, both film and ionization chambers were used in the mouse phantoms, while on Easy and George Shots only film packs were used, because of the limited number of ionization chambers available as detectors.

There were numerous mouse phantoms distributed throughout the cages wherever mice were exposed [1,2] so that dose data for these conditions are complete within the limits of detection by such film.

2.5 ARMORED-TANK PHANTOMS

Conventional-type phantoms were placed in various locations inside armored tanks to obtain measurements of surface and total-body dose received by the tank commander and the driver. These tank phantoms (Fig. 2.8) were 35-cm cubes of laminated masonite. Film packs were utilized for detection and were distributed throughout the phantoms in a manner similar to that employed in the swine phantoms. The tank phantoms were placed in the commanders' and drivers' seats in several tanks located at Stations E–6321 (750 yd), E–6323 (750 yd), E–6331 (1,000 yd), E–6343 (1,250 yd), E–6351 (1,400 yd), and E–6348 (1,250 yd) on Easy Shot.

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[1] Greenhouse Report, Annex 2.5, Part I.

[2] Part I of this report.

Chapter 3

Results

3.1 GENERAL DISCUSSION

Measurements made in the lucite spheres, and based on ionization-chamber readings, appear to be the most reliable. As originally predicted, whenever the film and glass were used their energy-dependent characteristics made it impossible to evaluate the depth dose with acceptable accuracy in time to be incorporated in this report. However, their data did prove to be of considerable value in confirming the slope obtained with ionization chambers in the dose vs distance curves. When a suitable X-ray generator is made available, the necessary control studies can be carried out to permit accurate evaluation of all film and glass data in terms of depth-dose response.

3.2 LUCITE SPHERES

Two stations, each of which incorporated a set of spheres containing ionization chambers, were set up for Easy Shot and all the instruments were recovered. Two such stations were also set up for George Shot. Unfortunately, however, only one station supplied data as the other was partly blown away and what instruments were recovered read off-scale.

Data obtained from the two stations on Easy Shot and the one station on George Shot are plotted in Fig. 3.1. The curves all appeared to be the same, and when they were normalized the maximum variation was ± 1.5 per cent at any point. The following information can be obtained from these curves: the absorption coefficient and mean free path in lucite and air, the equilibrium wall thickness in lucite, and the dose at two distances from ground

zero for Easy Shot and at one distance for George Shot.

The absorption coefficient and mean free path for the broad beam in lucite were obtained in the following manner:

Since
$$I_2 = I_1 e^{-\mu x} \qquad (3.1)$$

$$\mu = \frac{\ln I_1 - \ln I_2}{x}. \qquad (3.2)$$

From the composite curve of Fig. 3.1

$$I_1 = 84.6$$
$$I_2 = 65.3$$
$$x = 8.5 \text{ cm.}$$

Substituting in Eq. 3.2

$$\mu = \frac{4.43792 - 4.17897}{8.5}$$

$$= \frac{0.25895}{8.5}$$

$$= 0.03046 \text{ cm}^{-1}(\text{lucite}).$$

The mean free path in lucite is:

$$\lambda = \frac{1}{\mu} = 32.8 \text{ cm.}$$

The density of the lucite was 1.17 g/cc.

Assuming the density of the air at shot time to be 0.001154 g/cc

$$\frac{32.8 \times 1.17}{0.001154 \times 10^2} = 332.5 \text{ meters}$$

or

$$332.5 \times 1.094 = 364 \text{ yd.}$$

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The equilibrium wall thickness for the gamma radiation of the bomb appears to be 3 cm of lucite.

From Fig. 3.1, the dose of Easy Shot at 1,465 yd (Curve E_1) was 650 r and at 1,640 yd (Curve E_2) the dose was 286 r. For George Shot the dose at 2,160 yd (Curve G) was 433 r.

3.3 SWINE PHANTOMS

As stated in Sec. 2.3 the swine phantom data, at the time of writing this report, were of value only to supply additional information in determining the dose vs distance curve for Easy Shot. There were not sufficient data on George Shot to prove of any immediate value.

3.4 MOUSE PHANTOMS

An opportunity was presented on Dog Shot to test the ionization chambers along with the biomedical film and NBS packs. The effects of absorption and scattering under the conditions of exposure in this instance were small, and as can be seen in Fig. 3.2 (Curve D) the agreement of the three detectors was excellent.

The data from the mouse phantoms on Easy Shot fall in the same category as the swine phantom data, and they will prove valuable when time and equipment permit further control studies.

3.5 ARMORED-TANK PHANTOMS

The tank phantoms supplied data that permitted a calculation of the mean dose received by the commander and driver of an armored tank under various conditions. The results of this experiment are shown in Table 3.1.

3.6 DOSE VS DISTANCE CURVE AS SUMMARIZED FROM ALL AVAILABLE DATA

The dose vs distance curves for Dog and Easy Shots are shown in Fig. 3.2. Transposition of these curves into a log rd^2 vs d curve when the dose r is in roentgens and the distance d is in yards is shown in Fig. 3.3. There

were not sufficient data to establish a curve for George Shot; the one point where a reliable measurement was obtained is given in the last paragraph of Sec. 3.2.

3.7 REPRODUCTION OF THE GAMMA-RAY EFFECTS OF THE BOMB IN THE LABORATORY

Several sources of radiation were used in attempting to reproduce the effects of the bomb in the laboratory. The spheres, with ionization chambers in them, were exposed to a 2-Mev General Electric industrial X-ray generator, a high-intensity source of Co^{60}, a 10-Mev General Electric betatron and a 22-Mev Allis-Chalmers betatron. The results are shown in Fig. 3.4.

From these curves it is apparent that the 10-Mev betatron, used without added filtration, most accurately duplicates the bomb radiation in absorption characteristics. By personal communication, it has been learned that a comprehensive analysis of the spectral distribution from this source is being carried out by the NBS. When these complete data are available, a more accurate evaluation of the observed phenomena should be possible.

TABLE 3.1 AVERAGE BODY DOSE RECEIVED IN THE COMMANDERS' AND DRIVERS' SEATS OF ARMORED TANKS AT 750 TO 1,400 YD FROM GROUND ZERO, EASY SHOT

STATION NO.	DISTANCE (yd)	TANK SEAT	AVERAGE DOSE[a] (r)
E-6321	750	Driver	1,025
E-6321	750	Commander	1,180
E-6323	750	Driver	840
E-6331	1,000	Commander	690
E-6331	1,000	Driver	500
E-6343	1,250	Driver	32
E-6348	1,250	Commander	190
E-6348	1,250	Driver	300
E-6351	1,400	Commander	200
E-6351	1,400	Driver	80

[a] Owing to varying angular orientations of the individual tanks with respect to the source, absorption by armor plate of varying thickness, and by interposed portions of turret, machinery, etc., became of predominant importance in determining dose received.

Chapter 4

Discussion

The information obtained from the Japanese atomic bomb data seemed to indicate that the energy of the gamma radiation was considerably less than the calculated value. From a clinical standpoint, it was difficult to understand how some of the Japanese were epilated, when the dose required for epilation with a high-energy beam was considerably greater than that needed to produce 100 per cent mortality for total-body radiation. It was understood that factors other than the energy of the radiation might produce such an effect; however, since human experimentation would not be feasible the logical place to start, in attempting to explain this phenomenon, was to measure the effects of the gamma radiation in approximately unit-density material.

It was decided that techniques similar to those used in clinical radiology might give information sufficient to clear up the discrepancy, or at least to eliminate one of the possibilities. After the decision that measurements would be made in unit-density material, the question of what detector should be used presented itself. Past experience had shown that film was better as a detector in measuring the high-intensity gamma radiation produced by an atomic bomb than the ionization chambers used up to the time plans were being

promulgated for this operation. Film, however, was known to be energy dependent, and all attempts to use it for absolute depth-dose measurements in clinical X-ray therapy had failed.

It was decided, however, that film would be used in spite of its energy dependence, since, given a sufficient length of time, equipment could be developed to reproduce accurately the effects of the bomb on the film in unit-density material in the laboratory. It was also decided that attempts would be made to find or develop ionization chambers which could be used with the high-intensity source, since they had proven so successful in depth-dose measurements for the use of clinical radiologists.

Ionization chambers were procured which had a very high voltage gradient that should provide saturation voltage under the conditions of atomic bomb exposure; however, they could not be made by production methods so a very limited supply was available for use in the field. They supplied the information upon which most of this report is based. Film could have been used alone but it would have been considerably less accurate, and the submission of this report would have been further delayed by the necessity for exhaustively detailed calibration exposures.

Chapter 5

Conclusions

1. Experimental evidence has shown that the effective energy of gamma radiation from the bomb is quite high, as originally calculated, and that some other explanation for the observed epilation of the Japanese must be found.

2. The type of ionization chamber used in the spheres proved to be satisfactory for measuring the high intensity of gamma radiation emitted by the bomb.

3. Gamma-ray effects of the bomb can be reproduced in the laboratory by using an X-ray generator producing a beam with characteristics similar to that of the General Electric 10-Mev betatron at the Naval Ordnance Laboratory, White Oak, Maryland.

4. The curves showing dose vs distance on a semilog graph for Easy Shot are straight over a very limited portion of the curve. Fortunately these curves can be assumed to be linear in the portion of primary interest to the biomedical program.

5. Although there is not sufficient information from the data obtained in this experiment to definitely establish the fact, there is an indication that the negative slope of the dose vs distance curve increases toward the high-dose side and decreases on the low-dose side of the graph. The straight line of the curves (Fig. 3.2) from the least-squares fit of film data on Easy, the ionization-chamber curve on Easy, and the curves plotted from readings of the various detectors used on Dog Shot have similar slopes.

6. Finally, from the readings of the ionization chambers in the spheres (Fig. 3.1), it can be said that there was no apparent difference in the energy of the radiation from 1,460 to 1,645 yd on Easy Shot, nor any difference between the energy at these two distances on Easy Shot and that observed at the single 2,160-yd station on George Shot.

Chapter 6

Recommendations

6.1 RECOMMENDATIONS FOR FUTURE EXPERIMENTS

The data obtained in the present test indicate that several refinements should be made in future experiments:

1. Film should be replaced by ionization chambers in making depth-dose measurements in the phantoms.

2. A more complete absorption curve in approximately unit-density material should be obtained; probably by an increase in number and thickness range of the lucite spheres.

3. The effects of the radiation on unit-density material should be investigated over a wide range of distances and kilotonnage.

6.2 RECOMMENDATIONS FOR DEVELOPMENT OF EQUIPMENT

The limited number of ionization chambers used gave reliable data. It would, therefore, seem advisable to investigate the possibility of expanding their maximum range and of mass-producing them.

Although the 10-Mev betatron accurately reproduced the observed gamma radiation of the bomb, it is not a suitable machine for biological experiments. The possibility of developing a more suitable generator with greater uniform field area should be investigated, and if feasible one should be procured.

Some preliminary investigations have been started and progress has been made relative to development of the ionization chambers and the X-ray generator mentioned above at the Naval Medical Research Institute; however, additional support would be needed to carry the investigation to completion.
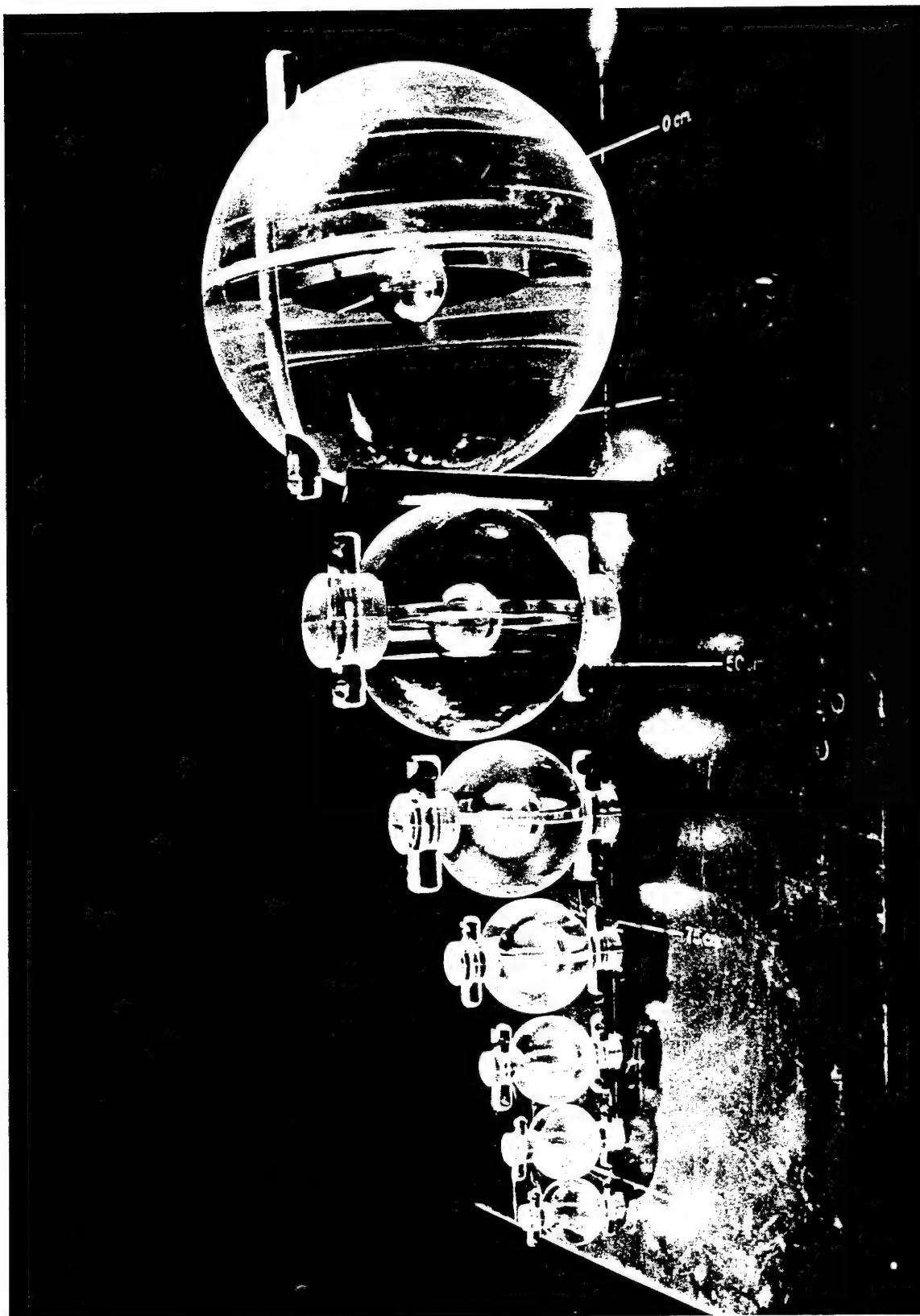
Fig. 2.1 Set of Seven Lucite Spheres
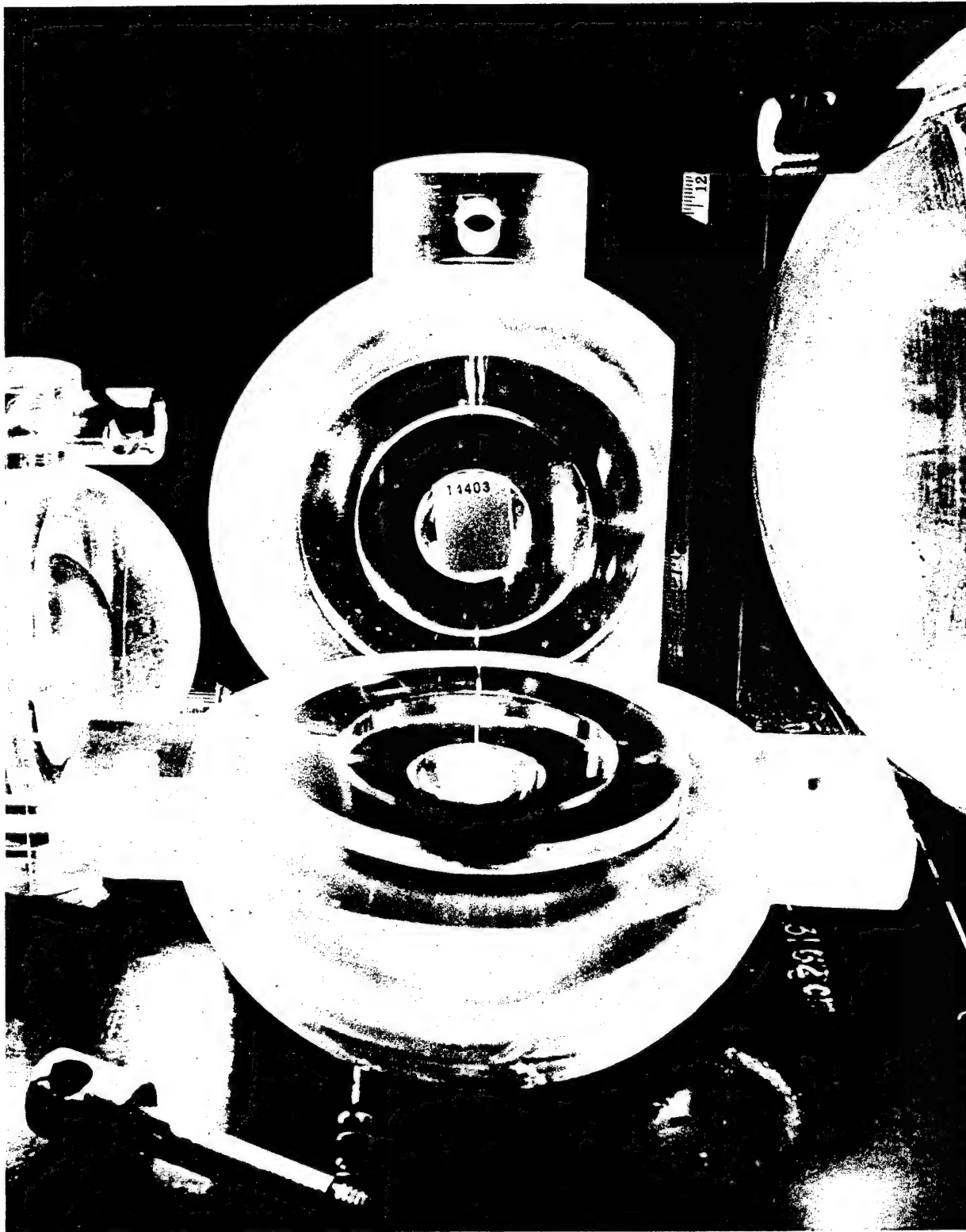
FIG. 2.2 Disassembled Sphere Showing Film Pack in Central Cavity
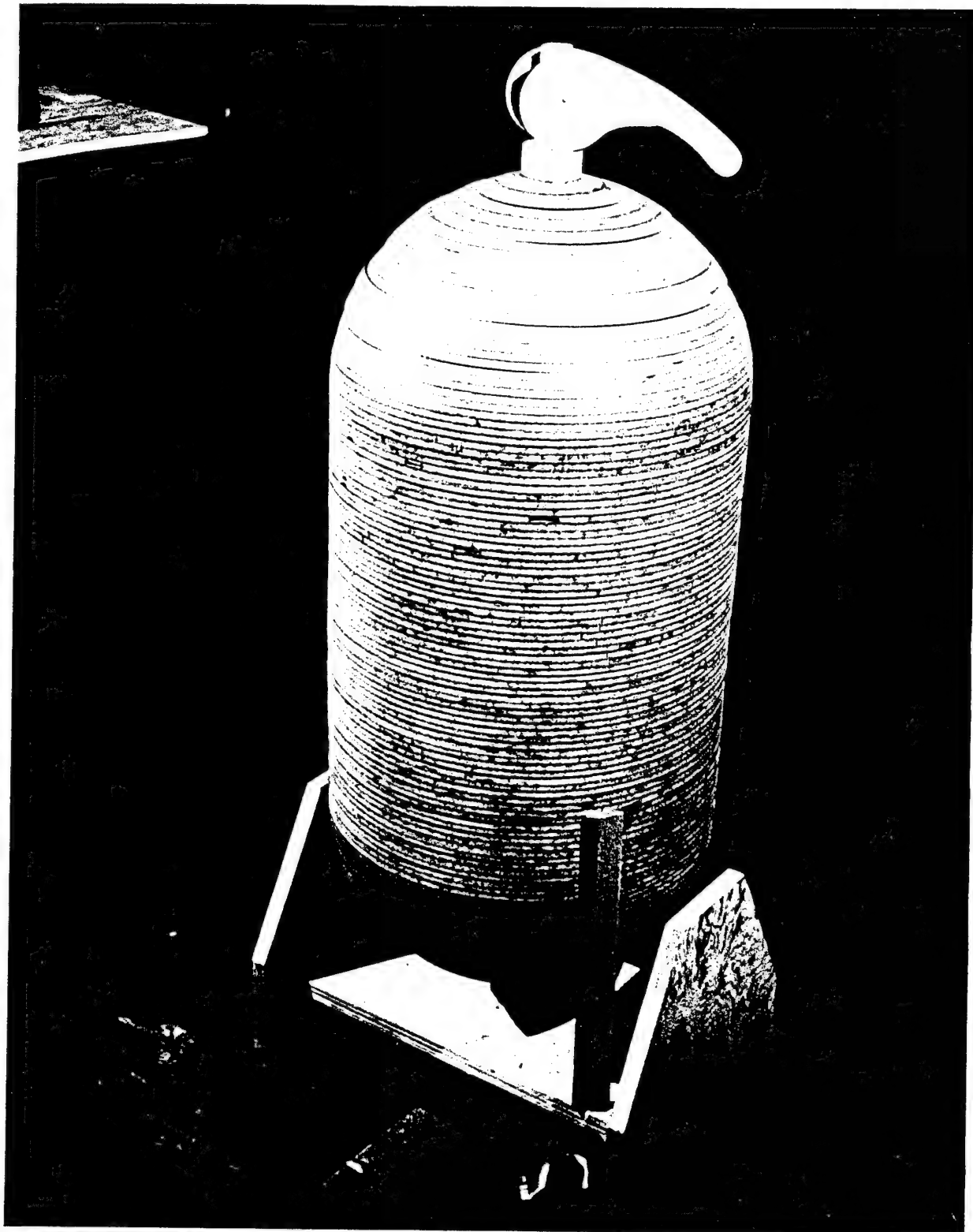
FIG. 2.3   Swine Phantom on Auxiliary Assembly Stand

2- MEV X—RAY SOURCE   605 FILM
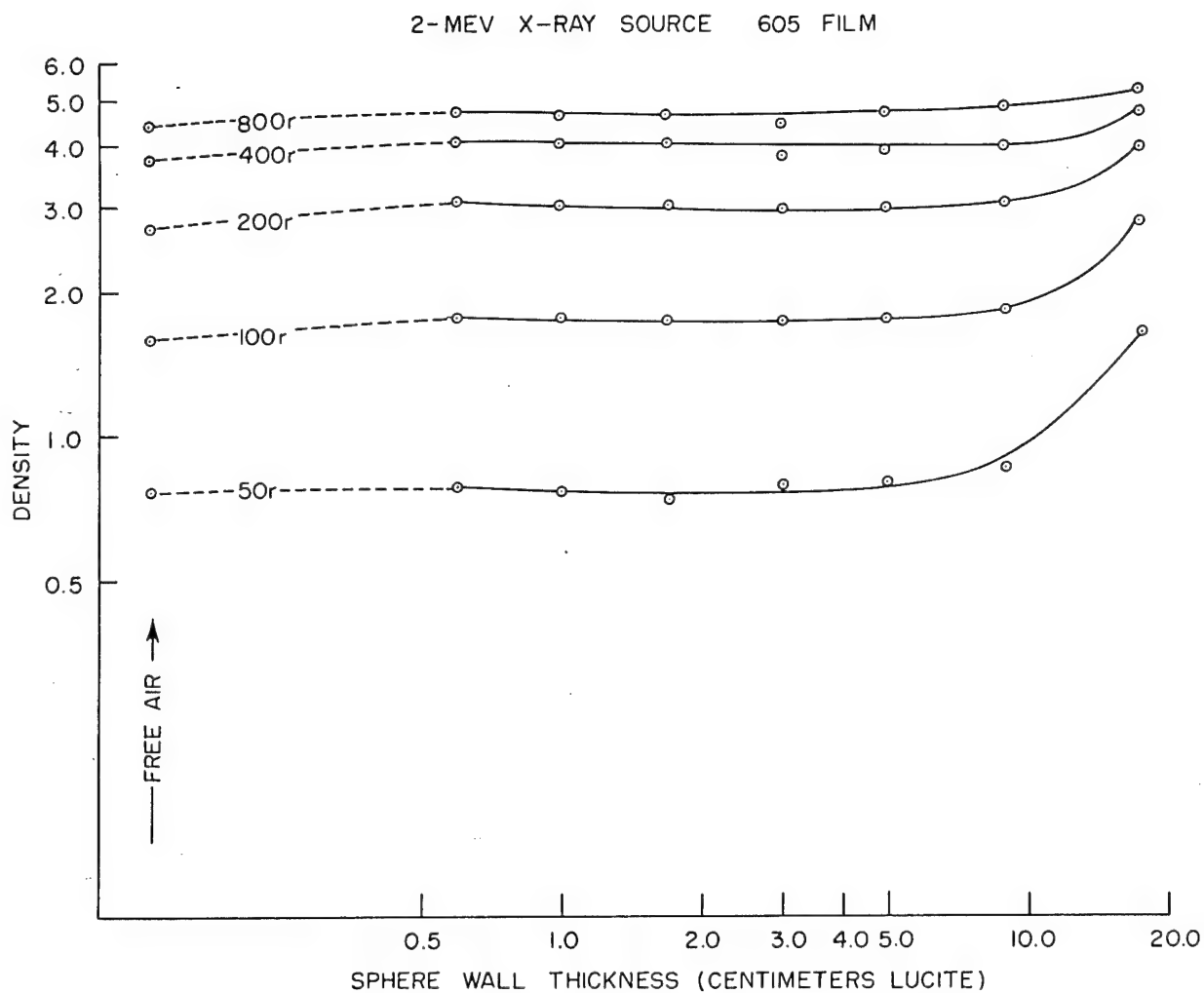
FIG. 2.4 Density vs Wall Thickness: No. 605 Film in Lucite Spheres, 2,000-KVP X-ray Source, 50- to 800-r Doses
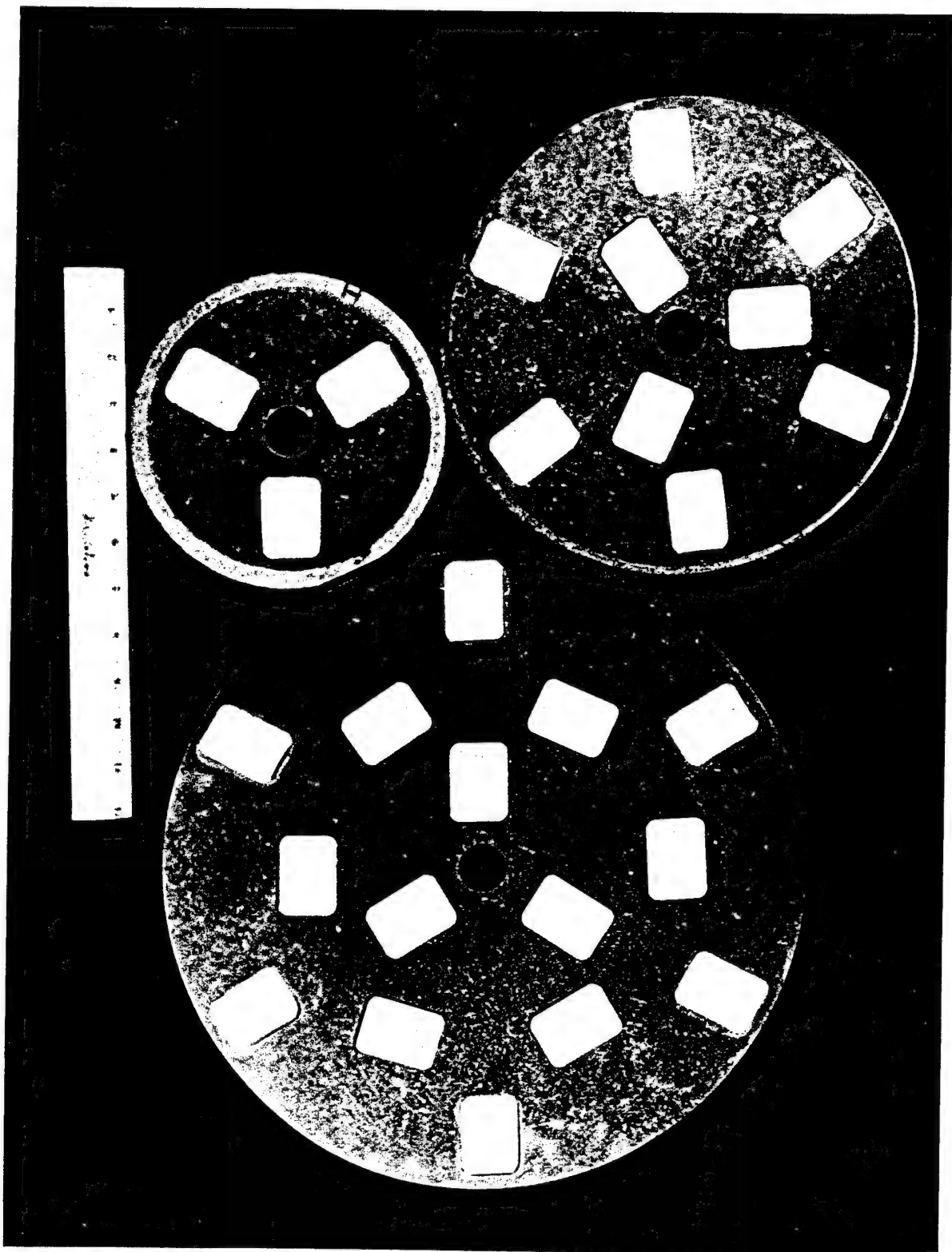
FIG. 2.5   Arrangement of Film Packs in Various Layers of Masonite Swine Phantom
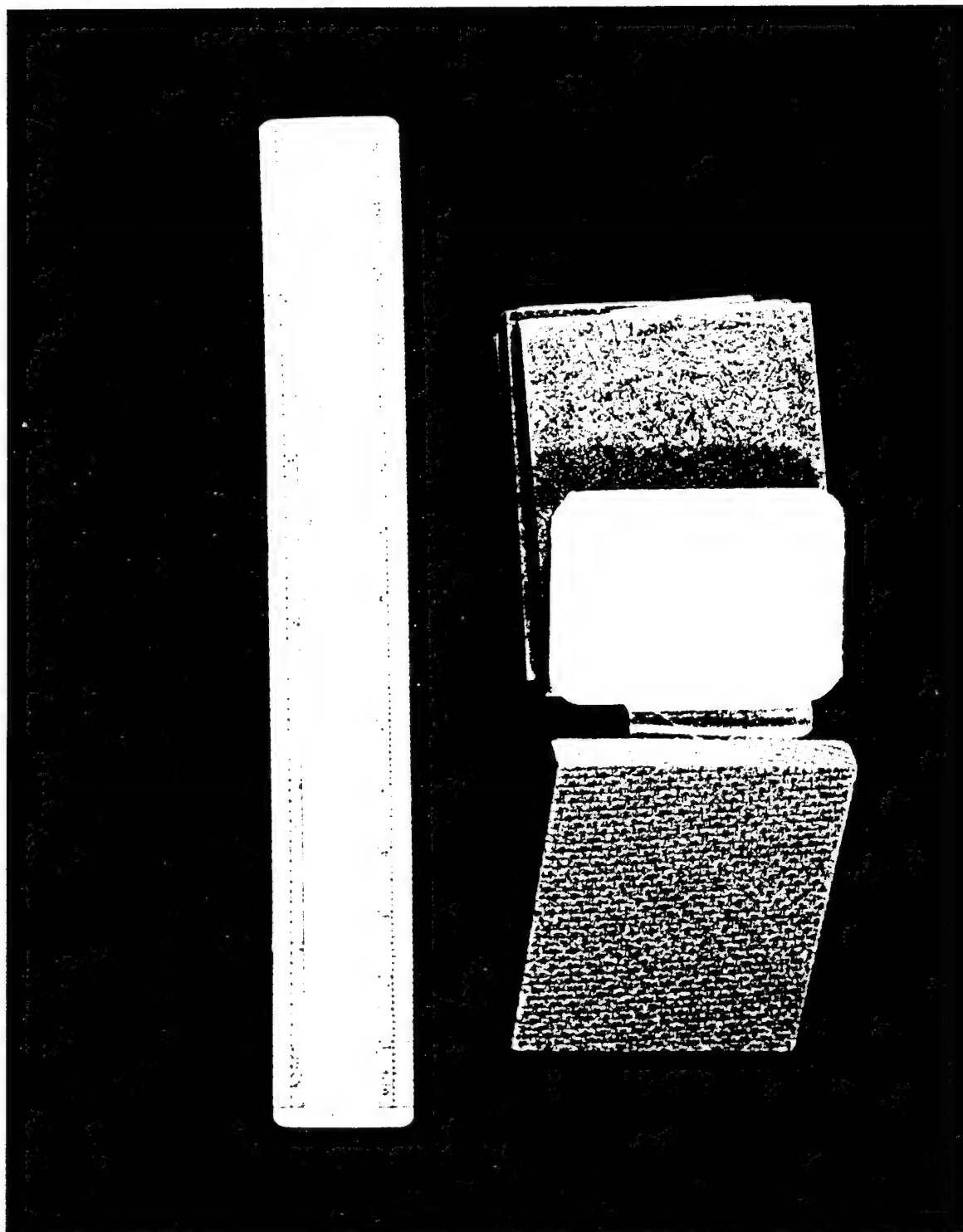
Fig. 2.6   Mouse Phantom Showing Placement of Film Pack
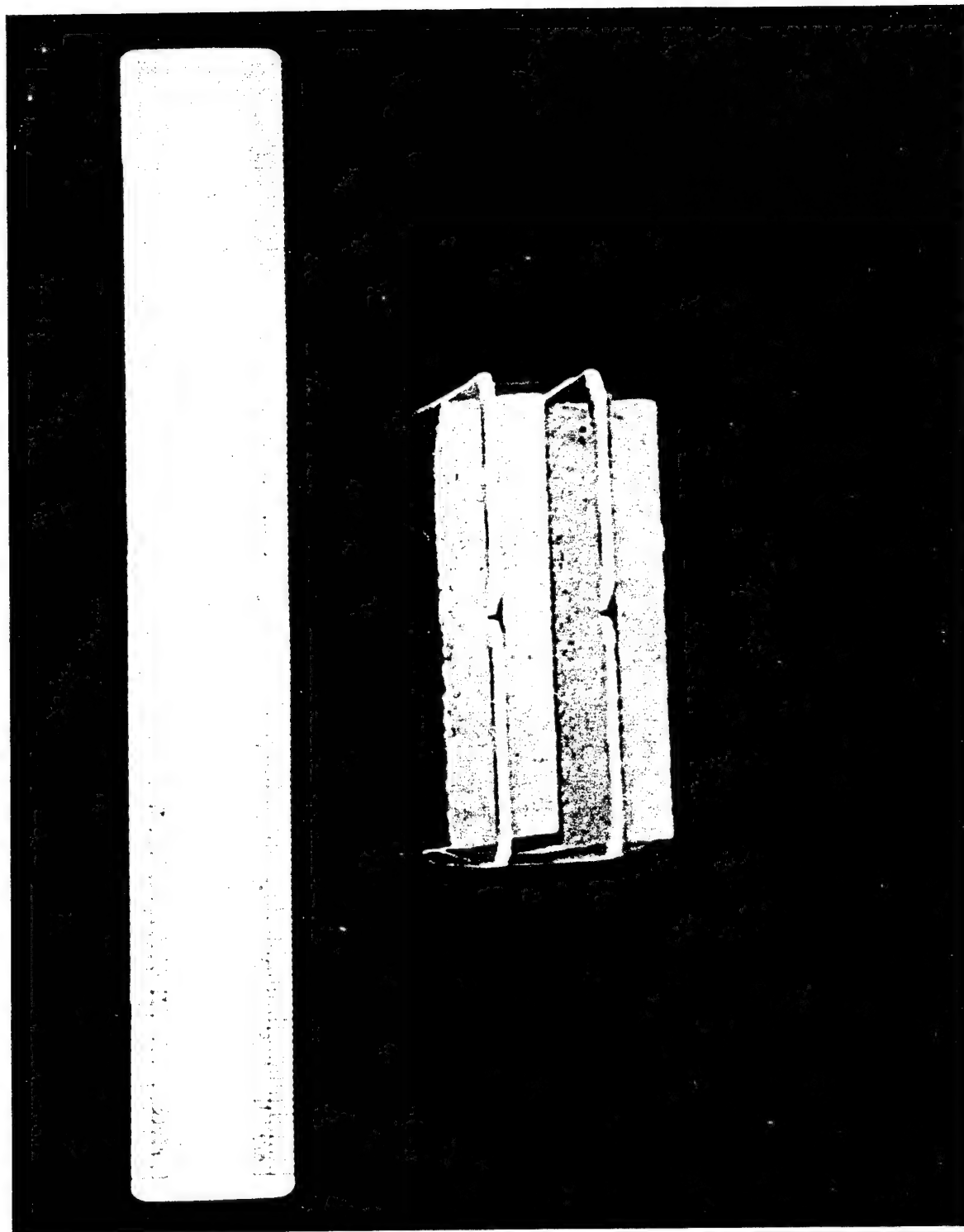
Fig. 2.7 Assembled Mouse Phantom Showing Film Packs between Layers of Masonite
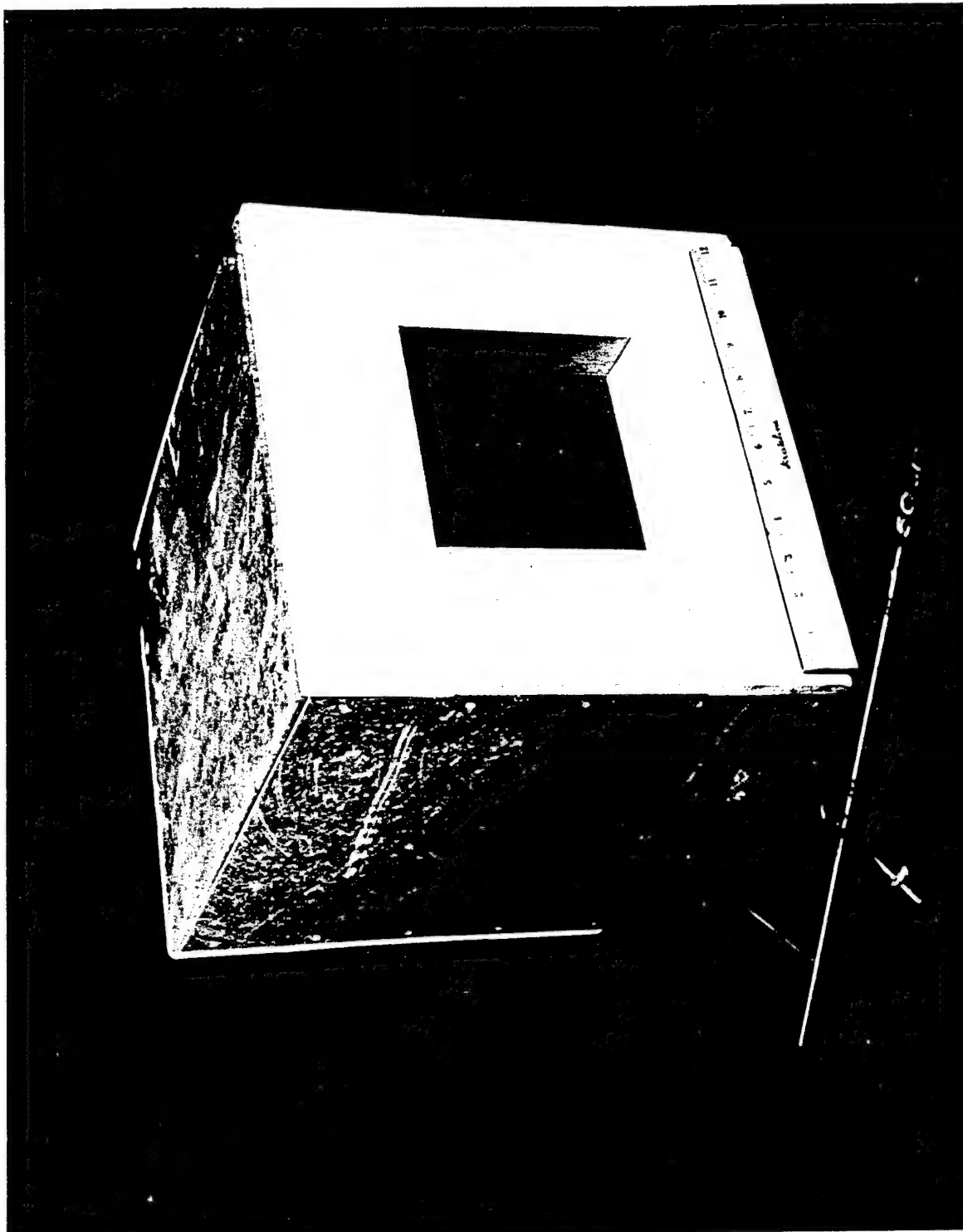
Fig. 2.8   Cubical Phantom as Used in Armored Tanks
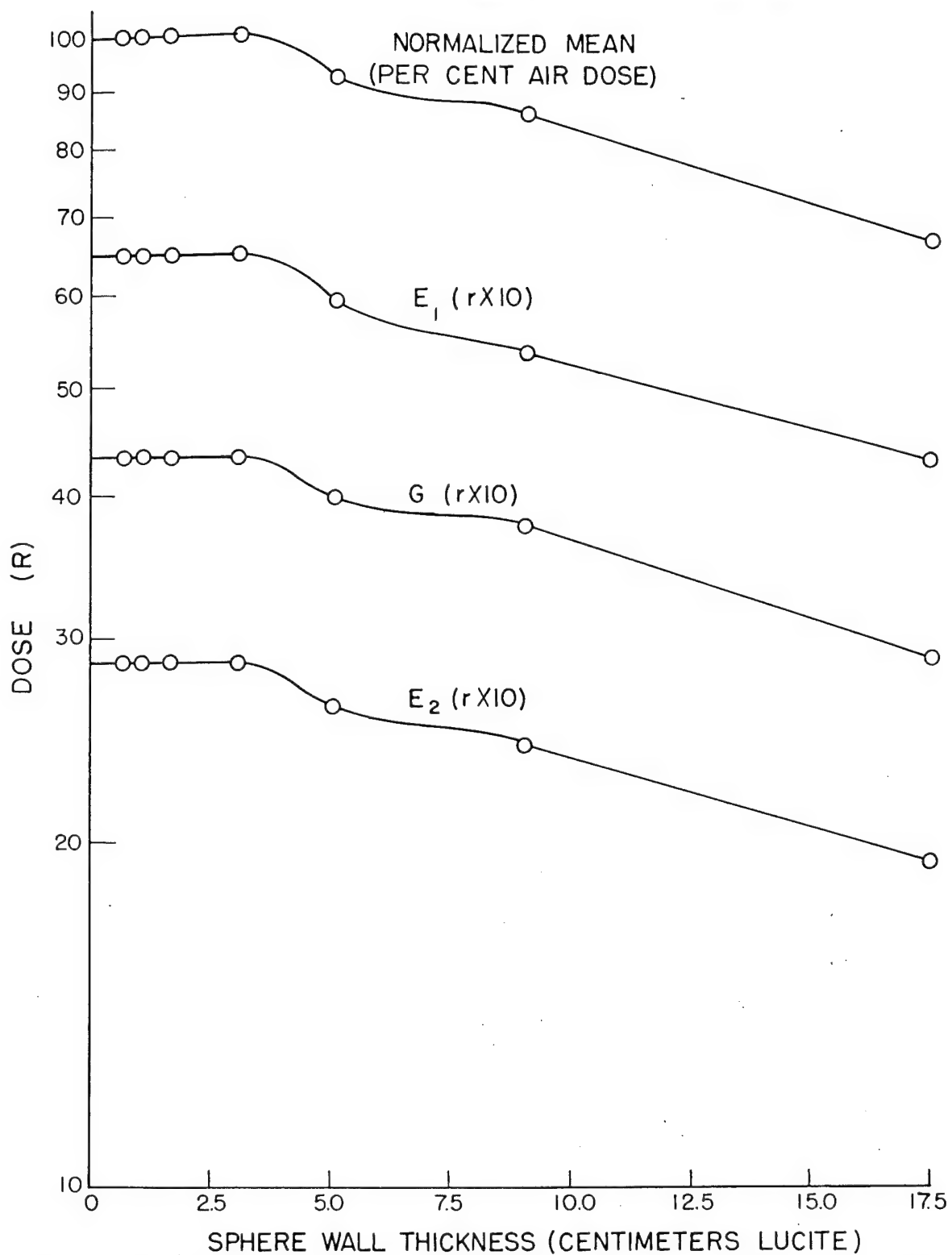
FIG. 3.1 Absorption vs Wall Thickness of Lucite Spheres from Easy (E) and George (G) Shots: E₁, 1,460 yd; E₂, 1,645 yd; and G, 2,160 yd
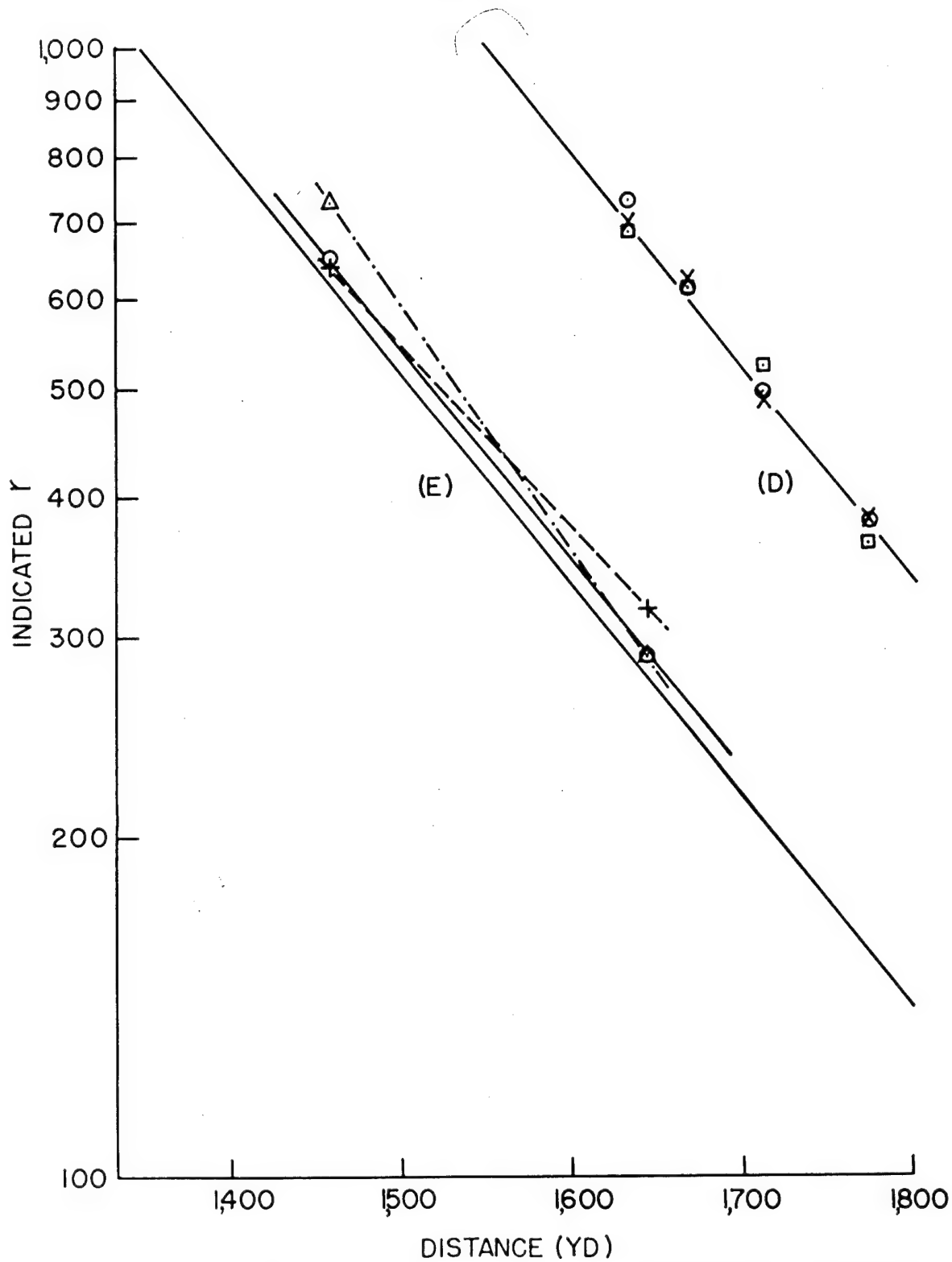
FIG. 3.2   Dose vs Distance Relations from Dog (D) and Easy (E) Shots: ▣ NBS Film, X Biomed Film. ⊙ Chambers, △ Glass.   The log unbroken curve is the least-squares fit for all film data on Easy.
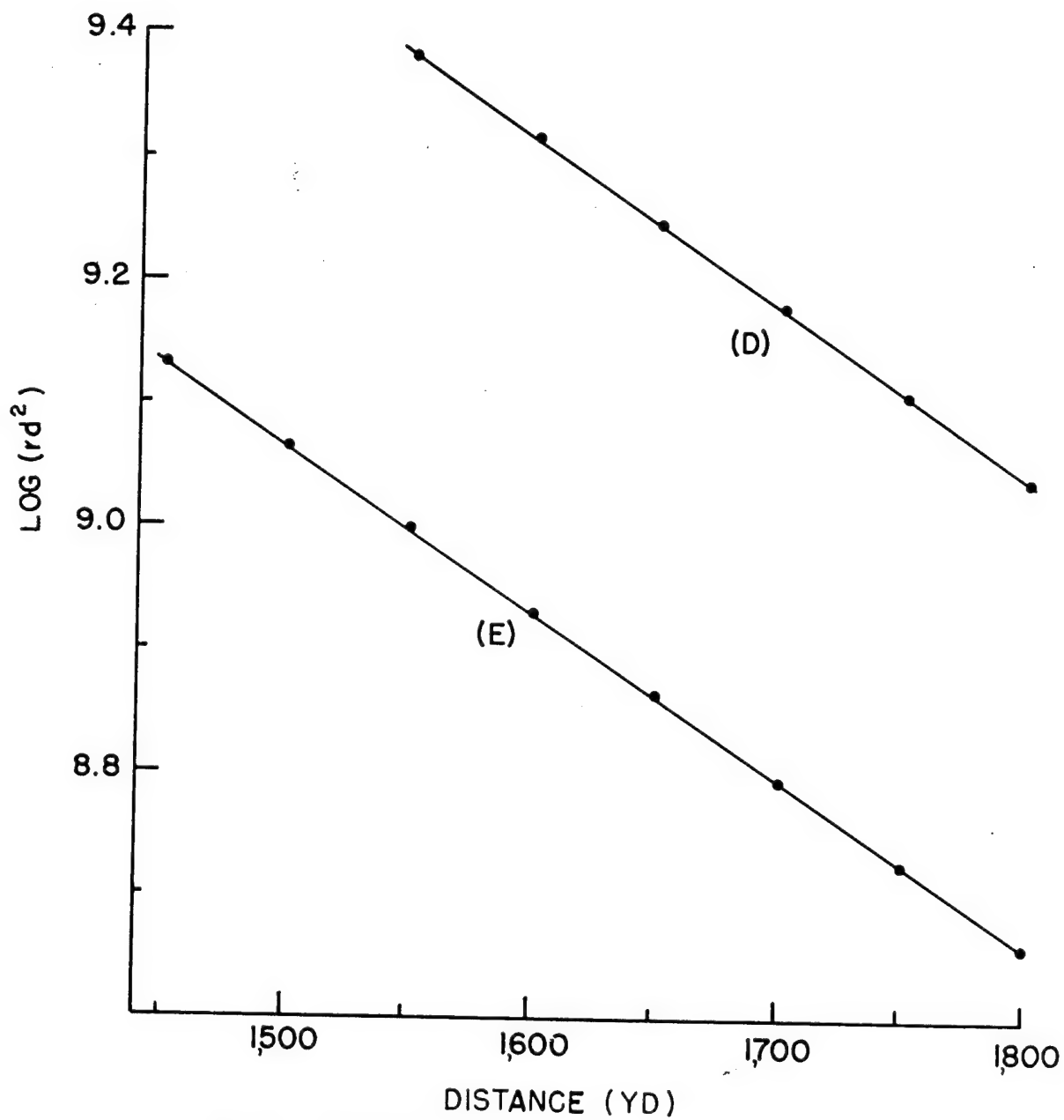
Fɪɢ. 3.3 Log (rd^2) vs d as Calculated from the Data of Fig. 3.2
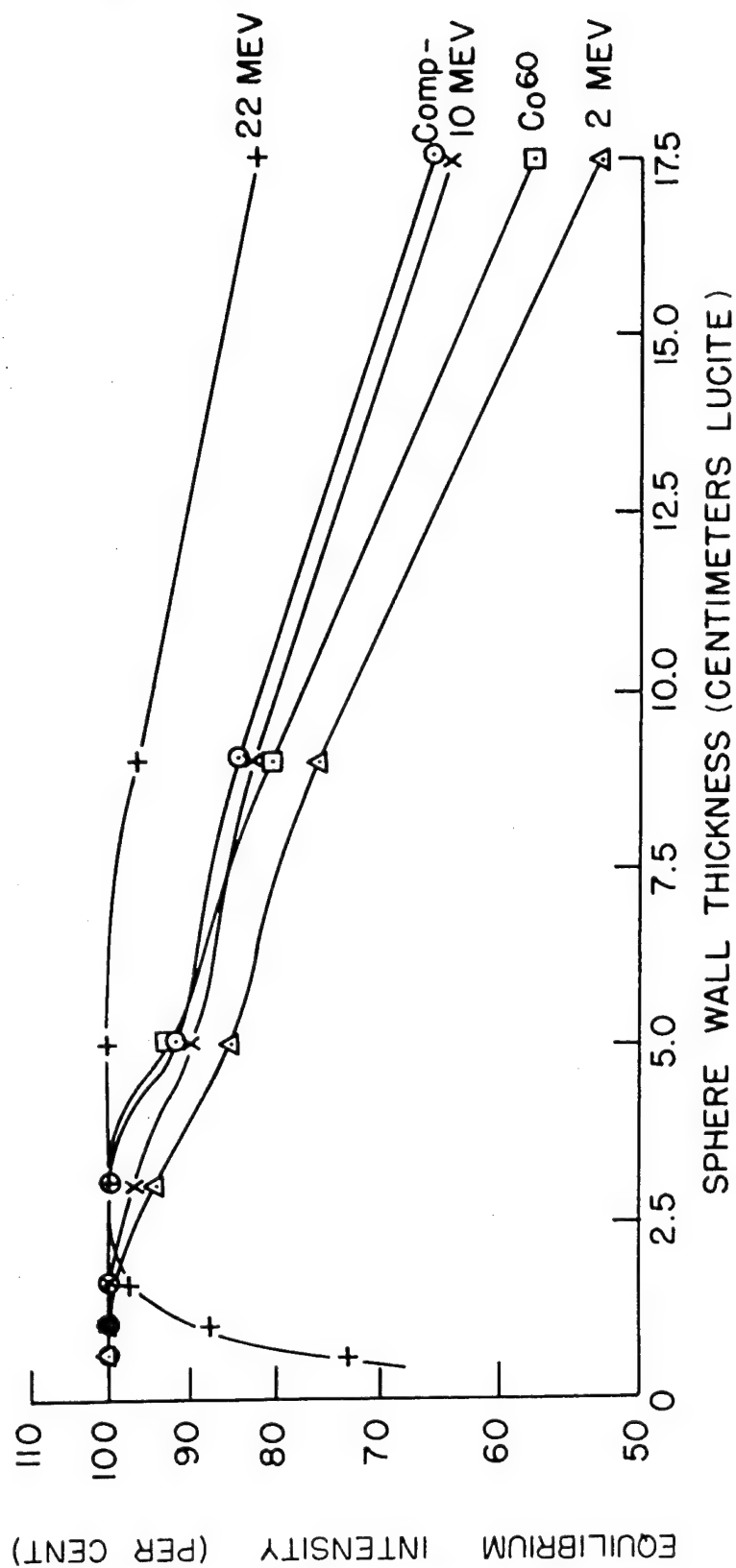
FIG. 3.4 Absorption in Lucite Spheres of Radiation from Various Sources, Including the Bomb

Part III

BIOLOGICAL DOSIMETRY OF ATOMIC BOMBS, USING *TRADESCANTIA*

by

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with the assistance of
Dorin S. Daniels and Lucile M. Fairchild

Abstract

Biological estimates of the radiation dose received from atomic bombs in drone airplanes and in gamma-ray and neutron stations on the ground have been made with the plant *Tradescantia*. Dose estimates were made by comparisons of the amount of chromosomal breakage caused in cells by bomb radiation with the amount caused by known doses of radiation. Dosage estimates by *Tradescantia* agree reasonably well with film and ionization-chamber measurements.

Chapter 1

Biological Dosimetry of Atomic Bombs, Using Tradescantia

1.1 INTRODUCTION

The flowering plant *Tradescantia* has been exposed to atomic bomb radiations in an attempt to use the plant as a biological dosimeter. The method is based on the quantitative relation between radiation dose and number of chromosomes broken in the cells of the plant. By comparing the amount of biological effect caused by the bomb with the amount caused by known doses of radiation (from the control experiments [1]) a biological estimate of dose is derived. Dosage estimates from *Tradescantia* data are compared with measurements made by radiation instruments exposed with or in similar situations to the plant; there is reasonable agreement between the two. No new or unique effects were detected in this bomb-irradiated material.

1.2 METHODS

1.2.1 Handling Material, Loading, and Recovery

Flower heads were picked from plants the morning of the day before a shot and packed into "irradiation units." The unit was a bundle of about 30 to 40 flower heads with the stems in a water-filled vial, the flower buds sticking out the top. The bundle of flowers was held in the vial with a strip of Scotch tape over the top. The flower buds, which are the biologically reactive tissue, were thus exposed unshielded. Irradiation units were loaded into the top layer, front row of the gamma

cylinder liners with the mice and in the middle between the mouse cages in the neutron hemisphere stations. A special unit of 30 to 40 flower heads packed in a corked 1-pint Dewar flask with chipped ice was prepared for the drone airplanes.

Irradiation units were taken to the shot island and loaded into the appropriate stations with mice on shot−1 day. They were recovered on shot day and returned to the Japtan laboratory; drone airplane units were similarly handled. In general, the *Tradescantia* units were handled with, and at the same time as, the mice with which they were exposed. Irradiated flower heads were unpacked after return to Japtan, put in fresh water in jars, and kept in the greenhouse until slides were made from them.

1.2.2 Preparation and Scoring of Slides

Aceto-carmine smear slides were made of the pollen grains from the flower buds at 21 to 24 hr and 4 days after shot. Slide making and the method of microscopic observation and scoring of the radiation-induced chromosomal aberrations in the cells have been described in the control report.[2]

1.2.3 Method of Analysis

Biological effect is measured as mean frequency of aberrations per cell by microscopic observation of the chromosomal aberrations found in cells from irradiated flower buds. It is desired to estimate the unknown radiation dose x' received at a station from the observed aberration frequency y' caused by it. This

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[1] A. D. Conger, "The Effect of Radiation on *Tradescantia;* Its Use for Biological Dosimetry," Greenhouse Report, Annex 2.2, Part IV.

[2] *Ibid.*

estimate is made by using the data from the appropriate control experiments in which the aberration frequencies y caused by known doses x of a standard control radiation have been measured. Aberration frequency is related to ionization dose as

$$y = a + bx$$

for the one-hit aberrations and,

$$y = d + ex + fx^2$$

for the two-hit, or exchange, aberrations which for more accurate statistical treatment is expressed as

$$\sqrt{y} = a + bx .$$

The solutions of these equations by least-squares fits to the control experiments data are presented in Table 1.1. The data and graphs can be found in the control report.[3] It is seen that the environment (temperature and pressure), the type of radiation (gamma rays or neutrons), and the intensity of radiation (of X rays and gamma rays only) all influence the yield of aberrations for a given dose of radiation. The influence of these factors is discussed in the control report and is readily apparent from an inspection of the graphs therein. It is sufficient to say here that these factors in the control and in the field experiments were similar enough so that intercomparisons are valid.

[3] *Ibid.*

The point estimate of radiation dose x' received at any one station is

$$x' = \frac{y' - a}{b} \qquad \text{(for linear cases)}$$

and

$$x' = \frac{\sqrt{y'} - a}{b} \qquad \text{(for quadratic cases)}$$

and the confidence interval for the doses may be obtained with a straightforward application of a method described by Mood.[4] The point estimates of dose and their confidence intervals from the various exposure stations are presented in Sec. 1.3. It is apparent that two independent point estimates of dose (*e.g.,* estimates from the one-hit and two-hit aberrations) derived from a single population of cells at a station should be roughly the same, and their confidence intervals should overlap. This is true for most cases; exceptions will be specifically mentioned as they occur.

In the following tables, dose estimates and their confidence limits are given and, where known, the dose measurements made by physical methods at the same stations are also given. The numbers of cells and aberrations observed, from which the dose estimates are derived, are given for each station. The statistical analysis of the confidence limits of

[4] A. M. Mood, *Introduction to the Theory of Statistics,* pp 300–301 (New York: McGraw-Hill, 1950).

TABLE 1.1   REGRESSION LINES TO THE CONTROL DATA, FROM LEAST-SQUARES FITS

TYPE OF RADIATION FOR COMPARISON	TABLE IN CONTROL REPORT	CHROMATID OR CHROMOSOME OBSERVATIONS	TYPE OF ABERRATION	$y = a + bx$ or $\sqrt{y} = a + bx$		
				y	a	b
X rays at high intensity; for gamma-ray cylinders (r)	1.2	Chromatid	One hit	y	0.00	0.0108
	1.2	Chromatid	Exchanges	$\sqrt{y}$	0.0217	0.00545
	1.2	Chromosome	Exchanges	$\sqrt{y}$	0.101	0.00194
	1.2	Chromosome	Deletions	$\sqrt{y}$	0.122	0.00234
Fast neutrons; for neutron hemispheres (n units)	1.3	Chromatid	One hit	y	0.436	0.199
	1.3	Chromatid	Exchanges	y	0.0585	0.0684
	1.3	Chromosome	Exchanges	y	0.0373	0.0351
	1.3	Chromosome	Deletions	y	0.0577	0.0496
Gamma rays at 0°C and 380 mm Hg pressure; for drone airplanes (r)	1.4	Chromatid	One hit	y	-0.00783	0.00640
	1.4	Chromatid	Exchanges	$\sqrt{y}$	0.0947	0.00268
	1.4	Chromosome	Exchanges	$\sqrt{y}$	0.0385	0.00162
	1.4	Chromosome	Deletions	$\sqrt{y}$	0.144	0.00162

those dose estimates assumes that the number of cells (and aberrations therein) observed for each station is approximately the same as the number observed in the control experiments at the same dose. This is not true in several instances, where the numbers observed in the field were considerably smaller than in the control experiments. In such unavoidable cases, where the number of cells observed in the field is small, the true error associated with a point estimate of dose is probably larger than the statistics would indicate. Where larger numbers are observed, the error is probably less.

1.3 RESULTS

1.3.1 Drone Airplanes

Flower buds were packed with ice chips in a corked Dewar flask for exposure in the filtered-air compartment in the drone airplanes. These flasks had been found to reduce the intensity of a hard X-ray beam (235 KVP, two half-value layers of copper) only 2 per cent, so the ionization dose received by the buds inside was about the same as outside the flask. Probably most of the ionization in the flowers was caused by gamma rays plus smaller amounts of hard beta rays, and only a small fraction was due to surface contamination of the airplane. The airplane made two passes through the stem or the cloud, generally spending about 10 sec within the cloud during each pass, and about 5 to 10 min between passes. Radiation was delivered at a rate of approximately 150 r/min or more. The results are given in Table 1.2.

TABLE 1.2 BIOLOGICAL OBSERVATIONS AND DOSE ESTIMATES IN DRONE AIRPLANES

A. Chromatid aberrations observed 21 to 24 hr after irradiation

SHOT	ALTI-TUDE (ft)	No. of Buds	No. of Cells	Normal No.	Normal Fract.	One-hit Cd.+Isocd. No.	One-hit Cd.+Isocd. Per Cell	Two-hit Exchanges No.	Two-hit Exchanges Per Cell	From One Hit Dose Est.	From One Hit 90% Conf.	From Ex-changes Dose Est.	From Ex-changes 90% Conf.
Dog	16,000	6	303	103	0.34	225	0.74	52	0.17	117	101–133	120	74–171
	18,000	9	332	160	0.48	148	0.45	56	0.17	71	54–87	118	75–167
	20,000	2	106	52	0.49	53	0.49	24	0.23	78	61–93	142	97–195
Easy	16,000	12	475	369	0.78	101	0.21	10	0.02	34	16–51	19	0–66
	18,000	13	371	212	0.57	171	0.46	27	0.07	73	56–89	66	14–112
	20,000	5	205	37	0.18	232	1.13	62	0.30	178	160–196	170	124–232
George	16,000	8	236	223	0.94	11	0.05	1	0.004	8	0–26	...	... ...
	18,000	14	317	293	0.92	22	0.07	1	0.003	12	0–30	...	... ...
	20,000	11	238	216	0.91	22	0.09	..	.....	16	0–33	...	... ...

B. Chromosome aberrations observed 4 days after irradiation

SHOT	ALTI-TUDE (ft)	No. of Buds	No. of Cells	Normal No.	Normal Fract.	Deletions No.	Deletions Per Cell	Exchanges No.	Exchanges Per Cell	From Dele-tions Dose Est.	From Dele-tions 90% Conf.	From Ex-changes Dose Est.	From Ex-changes 90% Conf.
Dog	18,000	5	201	167	0.83	20	0.09	14	0.07	101	65–137	139	108–169
	20,000	3	91	78	0.86	7	0.08	5	0.06	82	45–118	121	90–151
Easy	20,000	10	144	112	0.78	19	0.13	14	0.10	135	100–171	169	138–199

Since large numbers of slides and cells were analyzed from these drone airplane exposures, no inaccuracy can be attributed to small numbers of observations; the data are among the best that were obtained. One particular discrepancy in these drone airplane results needs to be considered. It will be noted in Table 1.2 that dose estimates from one-hit aberrations differ from the estimates from exchanges or deletions, one-hit estimates being lower in some cases and higher in others. This is explained as follows: one-hit aberrations increase linearly with dose and are independent of intensity; two-hit or exchange aberrations increase as a power of the dose and are dependent on intensity, more aberrations being produced at high intensity, fewer at low.

The control experiments made at 4.6 r/min are being compared with drone airplane exposures at variable and unknown dose rates, in which case the intensity-independent one-hit aberrations give the proper estimates of absolute dose.

Table 1.3 is a simplified summary of the dose estimates from Table 1.2, along with the dose measurements made by the NBS film packs exposed in the same containers with *Tradescantia*.

The agreement between dose estimates by *Tradescantia* and measurements by NBS film packs is quite good. There seems to be, in general, an increase in measured dose from 16,000 to 20,000 ft, but there is no correlation of dose with bomb yield. These haphazard variations are probably due to the uncertainty of exposure time and flight path of the drones as they pass through the cloud.

1.3.2 Neutron Hemisphere Stations

Tradescantia "irradiation units" were exposed in neutron hemispheres on Dog, Easy, and George Shots, but flower buds from George Shot died before slides could be made from them. The flowers were placed in a standard position in the center of the neutron hemisphere stations, between the small mouse cages. Neutron doses for the control experiments were measured in "n units," that amount of fast-neutron radiation producing the same amount of ionization in a 100-r Victoreen chamber as 1 r of gamma rays. Estimated doses from the field are also in n units. One n unit is equivalent to about 2 to 2.5 rep; and the biological efficiency of neutrons to X rays or gamma rays is from 3 to 5 times, making the over-all gamma-ray equivalent of 1 n about 6 to 12 r of X rays or gamma rays. No conversion of n units to neutron flux can be given; however, the two units vary proportionally. The range covered in these exposures (6 to 62 n) is approximately equivalent to 60 to 600 r of X rays or gamma rays. The neutron results are in Table 1.4.

It is seen that for most stations the dose estimate derived from the observation of "deletions" is lower than the estimate derived from "exchanges." It is a fairly common experience when slide preparations are poor (as those from the field exposures were) that fewer deletions are observed than when slides are good, and also, data from deletions are less reliable. This is understandable, for more than half of these deletions are small dot fragments which can escape microscopic observation in poor preparations; fortunately, exchanges are large aberrations which are seen

TABLE 1.3 DOSE MEASUREMENTS IN DRONE AIRPLANES BY
TRADESCANTIA AND NBS FILM PACKS
(Dose estimates are in roentgens)

ALTITUDE (ft)	DOG		EASY		GEORGE	
	Tradescantia	Film	*Tradescantia*	Film	*Tradescantia*	Film
16,000	117	112 and 104	34	35.5	8	4.5
18,000	71	66 and 62	73	54	12	11
20,000	78	80 and 84.5	178	135	16	18

TABLE 1.4 BIOLOGICAL OBSERVATIONS AND DOSE ESTIMATES IN NEUTRON HEMISPHERE STATIONS

A. Chromatid aberrations observed 21 to 24 hr after irradiation

SHOT	STA-TION NO.	DIS-TANCE (yd)	No. of Buds	No. of Cells	Normal		One-hit Cd.+Isocd.		Two-hit Exchanges		From One Hit		From Ex-changes	
					No.	Fract.	No.	Per Cell	No.	Per Cell	Dose Est.	90% Conf.	Dose Est.	90% Conf.
Easy	85f	1,300	6	173	6	0.04	376	2.17	156	0.90	8.7	3.6–265	12.3	10.1–15.5

B. Chromosome aberrations observed 4 days after irradiation

SHOT	STA-TION NO.	DIS-TANCE (yd)	No. of Buds	No. of Cells	Normal		Deletions		Exchanges		From Dele-tions		From Ex-changes	
					No.	Fract.	No.	Per Cell	No.	Per Cell	Dose Est.	90% Conf.	Dose Est.	90% Conf.
Dog	73h	1,300	4	97	52	0.54	34	0.35	24	0.25	5.9	2.9– 8.7	6.0	2.7– 9.0
	73g	1,200	2	116	26	0.24	74	0.64	73	0.63	11.7	9.0–14.4	16.8	13.9–19.7
	73e	1,100	5	176	6	0.03	352	2.00	202	1.15	39.2	35.8–43.0	31.6	28.5–35.2
Easy	85f	1,300	9	253	127	0.50	74	0.29	98	0.39	4.7	1.7– 7.5	10.0	6.8–12.8
	85e	1,100	13	550	45	0.08	597	1.08	552	1.00	20.7	18.1–23.4	27.5	24.5–30.8
	73h	1,000	7	210	1	....	551	2.62	361	1.72	51.8	47.6–56.5	47.9	44.0–52.6
	85d	975	2	64	0	....	232	3.62	141	2.20	71.8	66.1–78.7	61.6	56.2–68.0

equally well in poor or good preparations. The unusually poor condition of the slides from field experiments is not due to radiation, but is believed to result from the relatively high night temperature in the exposure cylinders. The slides from the control experiments were superior to those obtained from the field tests, which probably accounts for this difference in dose estimates from the two classes of aberrations observed in the same cells.

The dose estimates derived from exchange data are plotted against distance from ground zero in Fig. 1.1.

The graph indicates that neutron flux is decreasing exponentially with distance and that the neutron doses in n units were essentially the same for the two bombs, at least in the 975- to 1,300-yd range being considered, although the two bombs differed in yield by a factor of approximately 2. These results are in general agreement with the neutron measurements made by Program 1.

Over the range of *Tradescantia* analysis, the decrease in neutron flux behaves as an exponential with distance, and in any case exponential or inverse-square decrease would be indistinguishable over this range; the same is true for the gamma-ray analysis.

1.3.3 Gamma-ray Stations

Tradescantia irradiation units were exposed in five gamma cylinder stations and two radiac hemisphere stations on Easy Shot; flowers were also exposed in gamma stations on George Shot but no material survived for observation. The flowers were placed in the top front-end compartment of the gamma cylinder liners and in the front compartment of the radiac stations. The results of the biological observations and dose estimates of these gamma-ray stations are given in Table 1.5.

Table 1.5 — BIOLOGICAL OBSERVATIONS AND DOSE ESTIMATES IN GAMMA-RAY STATIONS

A. Chromatid aberrations observed 21 to 24 hr after irradiation

SHOT	STATION NO.	DISTANCE (yd)	No. of Buds	No. of Cells	Normal		One-hit Cd.+Isocd.		Two-hit Exchanges		From One Hit		From Exchanges	
					No.	Fract.	No.	Per Cell	No.	Per Cell	Dose Est.	90% Conf.	Dose Est.	90% Conf.
Easy	518	2,367	5	213	191	0.90	20	0.09	1	0.00	8.7	0–34.1	9.0	0.0–27.0
	517	2,242	10	275	232	0.84	33	0.12	6	0.02	11.1	0–36.6	23.1	2.3–39.8

B. Chromosome aberrations observed 4 days after irradiation

SHOT	STATION NO.	DISTANCE (yd)	No. of Buds	No. of Cells	Normal		Deletions		Exchanges		From Deletions		From Exchanges	
					No.	Fract.	No.	Per Cell	No.	Per Cell	Dose Est.	90% Conf.	Dose Est.	90% Conf.
Easy	71e	1,750	3	44	23	0.52	15	0.34	12	0.27	197	158–237	217	174–260
	71d	1,650	10	202	82	0.41	84	0.42	89	0.44	224	184–263	290	248–334
	71a	1,555	4	191	23	0.12	165	0.83	198	1.00	337	298–377	462	417–509
	70v	1,490	6	97	3	0.03	116	1.20	134	1.38	416	376–455	554	507–604
	70t	1,440	1	34	0	....	108	3.18	67	1.97	710	670–751	672	621–727

The same difference between the dose estimates from exchange aberrations and deletions that was noticed in the neutron data is apparent here, no doubt for the same reason—in poor slides exchanges are all detected, but deletions are in general harder to observe and give variable results. The dose estimates from exchange aberrations will be used as the more accurate ones.

It is possible to compare the dose estimates from biological materials in these gamma-ray stations with the measurements made by film packs or ionization chambers which were in the same cylinders or at the same distances. Figure 1.2 is a graph of the measured dose of gamma rays, in roentgens, against distance from ground zero. In this figure, a comparison is made of the measurements by chromosome breakage in *Tradescantia,* thymus weight loss in the mouse, NBS film packs inside and outside the cylinders, and ionization chambers.

The slopes of the curves for *Tradescantia,* ionization chambers, and film packs inside cylinders have been compared and do not dif-

fer significantly from one another at the 5 per cent level. The data for the other curves were not available for analysis.

The biological estimates of dose by *Tradescantia* and mouse thymus weight loss are about 10 to 15 per cent apart in absolute units which is within the range of error of the two methods. *Tradescantia* dose estimates are closer, in absolute units, to the measurements by ionization chambers than to the mouse thymus or film-pack measurements made inside the cylinders.

1.3.4 Specific Control Experiments

Since the dose estimates are based on a comparison between the amount of chromosomal breakage caused in the field by a bomb and the amount caused in the control experiments made at Oak Ridge as much as 7 months perviously, a few specific control experiments were made to be certain the plant had not altered its response to radiation. Three general situations were tested. In the first, cells from plants in the Japtan Island greenhouse were examined to determine if the spontaneous

rate of chromosome breakage had been increased. No increase was found. In the specific control experiments, flowers were handled just as they would have been for a bomb test. They were loaded, along with the mice, into stations on the shot island, left overnight, recovered, and returned to Japtan the next day, where about half were analyzed to see if the specific environmental conditions had increased the spontaneous chromosome breakage rate. They had had no effect. The other half were given measured doses of X rays at Japtan, and the amount of chromosome breakage was compared with the amount caused by the same dose of X rays given at Oak Ridge. Agreement was quite good. Results of these control experiments are given in Table 1.6.

The environmental conditions have not caused any chromosome breakage, and neither have the methods of handling used for the bomb tests. It is gratifying that a dose of

X rays given at Eniwetok under the specific conditions of the bomb tests produced about the same effect as it did in Oak Ridge and that in a sample experiment of this sort (a test of the methods of analysis being used on the bomb data) there is such good agreement between the estimated dose and the known actual dose. This can be seen in the experiment of 16 April, where a dose of 100 r of X rays at Eniwetok is estimated biologically as 99 and 107 r from the Oak Ridge data.

1.4 CONCLUSIONS

1.4.1 Gamma Rays

Two conclusions of practical importance can be made from the *Tradescantia* dosimetry of atomic bomb gamma radiation: (a) bomb gamma radiation causes the same biological effects as X rays or gamma rays administered under laboratory conditions, and (b) physical

TABLE 1.6 CONTROL EXPERIMENTS IN THE FIELD

DATE	TREATMENT	No. of Buds	No. of Cells	Normal No.	Normal Fract.	Deletions No.	Deletions Per Cell	Exchanges No.	Exchanges Per Cell	From Deletions Dose Est.	From Deletions 90% Conf.	From Exchanges Dose Est.	From Exchanges 90% Conf.
26 April	None: slides made directly from plants in greenhouse	3	122	122	1.00	0	.....	0	.....				
11 May	None: slides made directly from plants in greenhouse	4	361	358	0.99	3	0.008	0	.....				
16 April (Specific control)	No radiation: flowers from neutron station	2	313	313	1.00	0	.....	0	.....				
16 April (Specific control)	No radiation: flowers from gamma-ray station	2	183	183	1.00	0	.....	0	.....				
16 April (Specific control)	100 r of X rays administered after flowers returned from gamma-ray station	2	200	155	0.78	28	0.14	17	0.085	107	68–147	99	55–141
2 May (Specific control)	135 r of X rays	7	246	178	0.72	43	0.175	43	0.175	127	87–165	163	120–206

measurements (by ionization instruments and films) and biological measurements (by *Tradescantia*) of bomb gamma radiation and of hard X rays are equal to each other. It seems fair to say that equal amounts of bomb or laboratory gamma-ray ionization, as measured by an ionization instrument, will produce the same amount of effect in *Tradescantia*.

The suitability of *Tradescantia* for biological dosimetry of gamma radiation is due to a number of factors:

(a) The plant exhibits the same amount of chromosome breakage for the same ionization dose at different times (7 months apart) and places (Oak Ridge and Eniwetok) and under different climatic conditions (see Sec. 1.3.4 and Table 1.6). This reproducibility has been observed in the past between experiments done in England and the United States, as much as 5 yr apart. The ordinary environmental range of temperature, humidity, and growing conditions (which may be quite wide) affects the radiation response but little. Even under the extreme conditions of 0°C and a pressure of 0.5 atm experienced in the drone airplanes, *Tradescantia* and ionization chambers or films measure dose equally (Table 1.2) when *Tradescantia* is calibrated under these conditions.

(b) Previous experience indicates that *Tradescantia* response is only moderately energy dependent in the range from ~ 40 kev X rays to hard gamma rays. X rays of 40 kev were found to be about 10 per cent more effective than gamma rays of 1 Mev or greater. One would be safe in allowing for not more than 25 per cent difference in the energy range just cited.

(c) Although *Tradescantia* response to electromagnetic radiation is dependent on *intensity* at rates below about 300 r/min, the aberration frequency-dose relation increasing from a linear minimum at low intensity to a dosage-squared maximum at about 300 r/min, any further increase in rate above 300 r/min is without effect. When the bomb's gamma flux is in excess of the rate necessary to produce maximum effect, intensity considerations can be ignored. It is significant that, in spite of the very high intensities at the closer distances, there was no evidence of any "biological saturation" (in the sense that an ionization chamber saturates if at high intensities it fails to collect ions completely). At the closest station, gamma-ray intensity from the bomb was about 350 times as great as in the control experiments, yet the measured effect vs distance does not depart from the exponential curve (Fig. 1.2).

(d) In comparison with most radiation effects studied in living material, *Tradescantia* response is so simple that it is not surprising that the plant and ionization instruments measure doses almost equally. A chromosome is broken only by a particle that goes through or very close to it, so the physical event (ionization) and its effect (chromosome breakage) occur in the same cell within a very short time and space and are not separated by a long chain of biological events which may occur elsewhere in the organism.

The fast-neutron contribution to the ionization dose in the gamma-ray stations is probably small. The very best situation for estimating this from the data is at the more distant lower dose stations, in which any appreciable amounts of neutron contamination would cause spuriously high dose estimates, owing to the linear response to neutron dose and geometric increase with gamma rays. Since the dose estimate-distance curve does not depart from an exponential relation at the lower doses, and these estimates are based on the assumption of a pure gamma-ray beam, the insignificance of the neutron dose at the gamma-ray stations seems quite certain.

It can be shown by another method that, in the 1,440- to 1,750-yd gamma-ray range surveyed by *Tradescantia,* neutrons could account for but a small fraction of the biological effect. Figure 1.3 is a graph of the estimated dose vs distance curves for gamma rays in roentgens and neutrons in n units for Easy Shot. A third curve is an estimate of the roentgen dose of gamma rays required to produce the same amount of *Tradescantia* damage as that caused by neutrons in the 1,440- to 1,750-yd range. This curve is derived from the neutron dose-distance curve by the conversion 1 n

unit ≈ 8.8 r of gamma rays (1 n$=$2.5 r in ionization, and for equal ionization the relative biological effectiveness of neutrons to gamma rays is 3.5 to 1) and the assumption that neutrons continue to decrease in the same way beyond 1,300 yd. The assumption is a conservative one; neutrons probably decrease more rapidly.

A comparison of the gamma-ray dose curve with the calculated gamma-ray dose equivalent curve from neutrons shows that neutrons produced only about $\frac{1}{25}$ as much effect as gamma rays in the 1,440- to 1,750-yd range on Easy Shot. Since this value is derived from observations of biological effect, the data are good evidence that gamma rays are still destructive out to distances at which neutrons are biologically insignificant for the Easy type bomb.

1.4.2 Fast Neutrons

The conformity of neutron-dose estimates to an exponential relationship with distance indicates two things: (1) that *Tradescantia* is measuring dose properly, and (2) that there can be no appreciable contribution from gamma rays, or the closer stations would show greater effect than the extended exponential curve.

Available data on neutron energy dependence of *Tradescantia* indicate that 3-Mev neutrons may be about 3 to 3½ times as effective as 15-Mev neutrons; *i.e.,* efficiency is inversely related to energy. However, the influence of neutron energy dependence is believed minimized in these experiments by using uranium fission neutrons for the control studies, the same as the bomb.

Expression of neutron dose in terms of an X-ray dose that would cause equivalent effect is rather difficult but it can be done for *Tradescantia* by the method previously employed in Sec. 1.4.1. The principal uncertainty is in the physical conversion of n units into roentgens and is related to the behavior of the Victoreen instrument in measuring neutrons. The plant itself is quite reliable and consistent, more so than the instrument, and has all the advantages for neutron dosimetry that apply to gamma rays, such as uniformity of response, plus the additional advantage that effect increases linearly with neutron dose and is intensity independent. The present data relating effect to a neutron dose unit which is proportional to flux will probably be quite adequate for future interpretations of effect vs absolute neutron flux at whatever time, by physical calibration, the present units can be expressed accurately as flux.
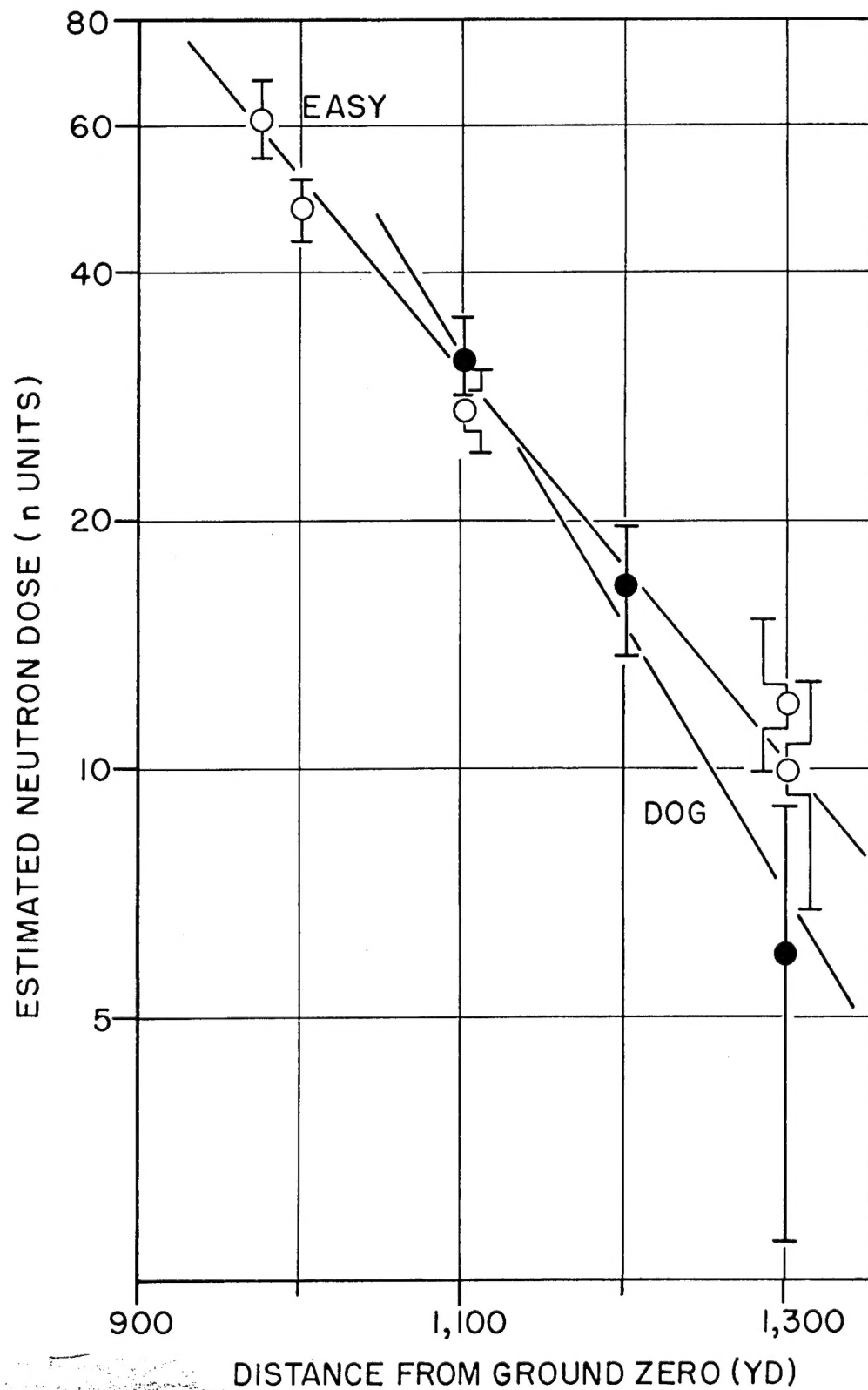
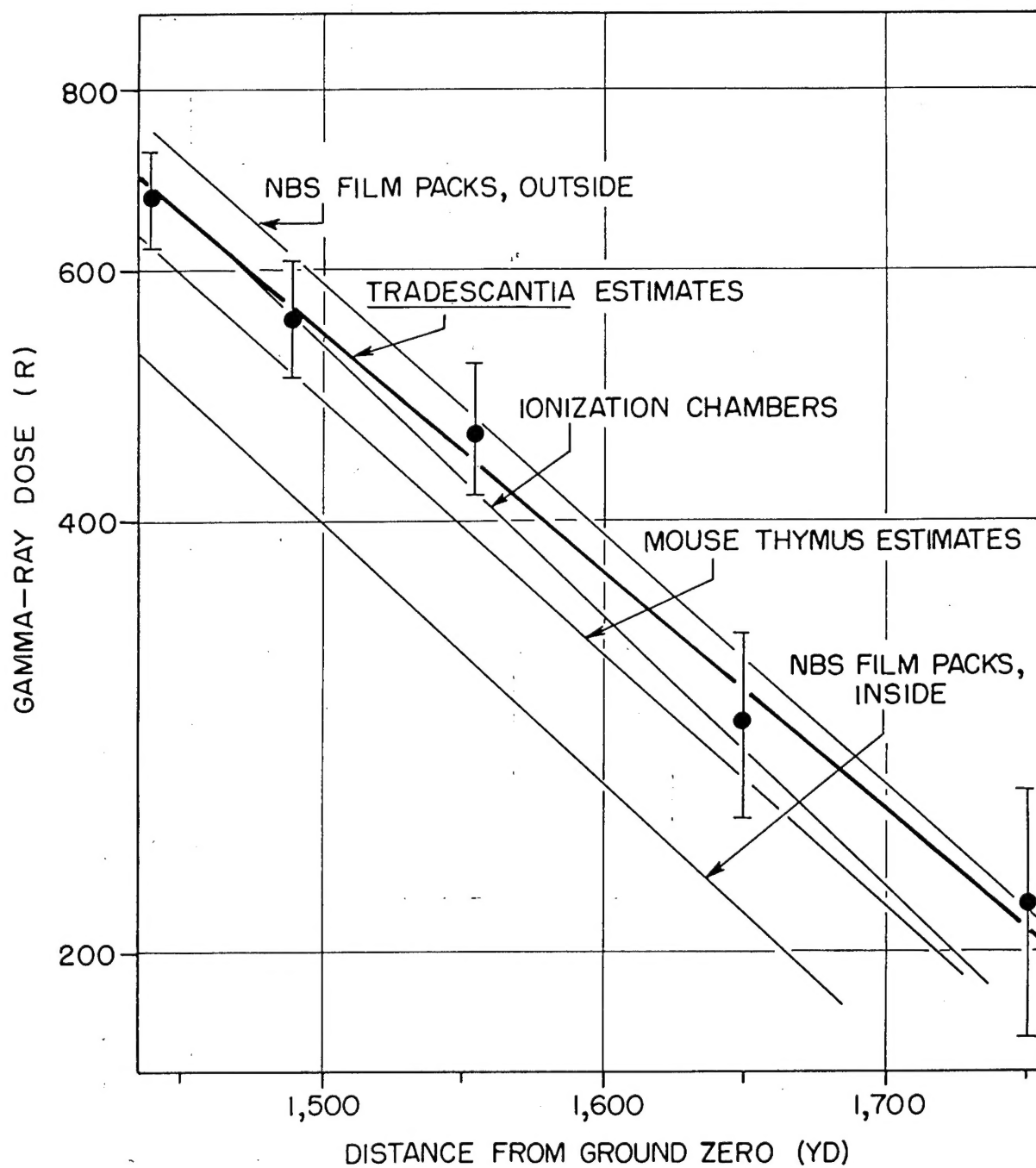FIG. 1.1 Neutron Dose vs Distance, Dog and Easy Shots

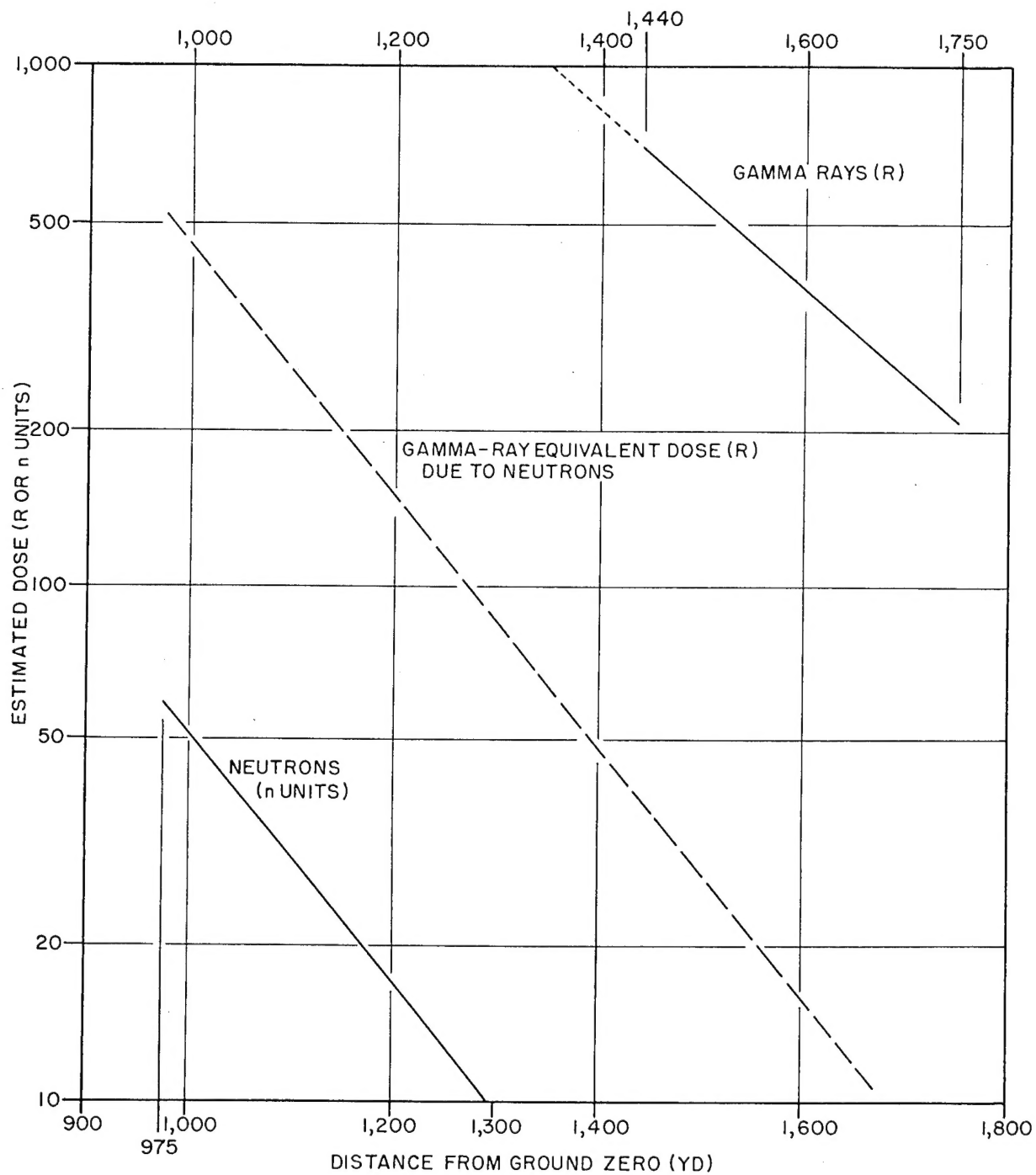FIG. 1.2 Gamma-ray Dose vs Distance, Easy Shot

FIG. 1.3 Neutron Dose (n units), Gamma-ray Dose (roentgens), and Estimated Gamma-ray Equivalent Dose (roentgens) due to Neutrons vs Distance, ~~Easy S~~